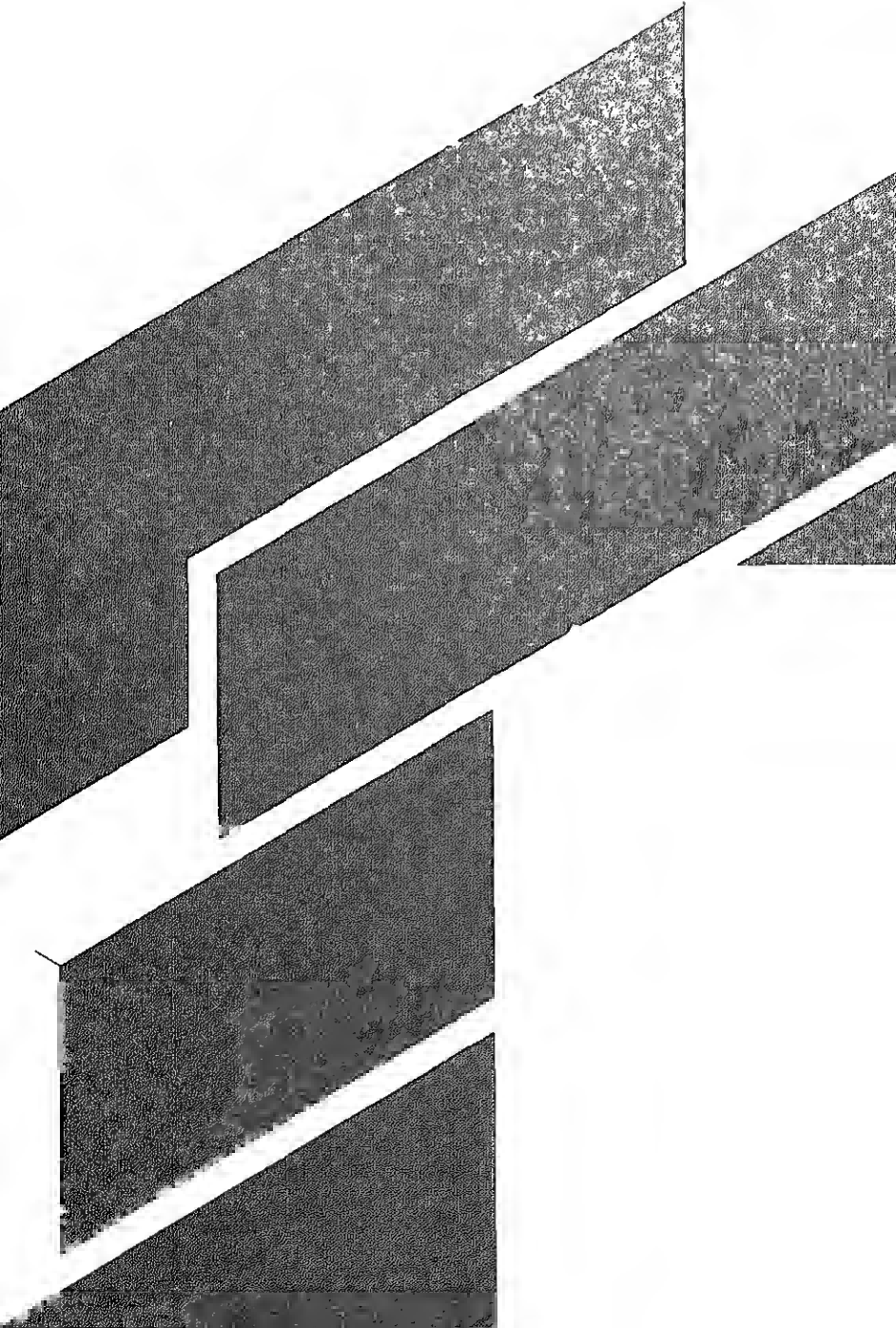




# Construction of Large-Panel Structures

## Report B "Horizontal Joint Tests"



**DESIGN AND CONSTRUCTION  
LARGE PANEL CONCRETE STRUCTURES**

Contract

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supplement

Horizontal Joint

No.

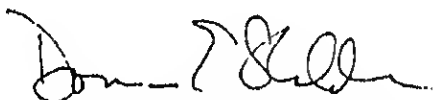
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## FOREWORD

Traditionally, multi-story buildings are so constructed that if a load-carrying member collapses, the entire structure does not: it has an inherent structural integrity. Construction using large-panel concrete members is not traditional. Builders cannot necessarily depend on a new structure's inherent integrity.

To avoid potential problems, the Office of Policy Development and Research has undertaken an extensive research program on large-panel concrete structures. Report No. 6, the sixth of nine, deals with horizontal joints, and most importantly with the connection of walls to floors.

The research program was supervised for HUD by the late William J. Werner and continued by Ronald J. Morone. Engineers, manufacturers, and builders have reason to be grateful to them.



Donna E. Shalala

Assistant Secretary for Policy  
Development and Research

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report describes full-scale tests conducted on horizontal to investigate the behavior of wall-to-floor connections in structures. Splitting tests were also made to determine the effect of reinforcement in the ends of the walls to limit splitting. Variables included in the test program were strength of grout, amount of transverse wall reinforcement, and presence of axial load and rotation. Effects of test variables on joint strength were determined and a design procedure is proposed.

Experimental report on horizontal joints is part of a series  
to the development of a "Methodology for the Design and Construction of  
Panel (LP) Structures." The objective of the tests described  
was to investigate the behavior of interior and exterior  
connections in LP structures.

Full-scale joint tests and seven splitting tests were made.  
The full-scale test consisted of an assembly of precast hollow-core floor  
slab and concrete wall elements forming a wall-to-floor connection.  
The wall element represented a short length of wall from a large panel.  
The floor slab was used to fill the joint between the ends of the floor slab.  
The effect of vertical load through the joint was investigated by applying  
compressive force in increments.

Simplified splitting tests were made on specimens consisting of  
a wall element loaded to represent partial surface loading.  
The objective was to determine the optimum amount of reinforcement  
in the ends of the wall panels to limit splitting.

The experimental program included the following controlled test variables:  
- strength of grout in the joint,  
- amount of transverse wall reinforcement,  
- grout-filled or unfilled slab cores, and  
- applied floor moment and rotation.

The compressive strength of concrete used in the wall panels and floor  
slab elements was held constant.

Based upon the provided combination of test variables mentioned above,  
the following damage patterns were observed at ultimate load:

- grout crushing,
- wall splitting, and
- slab crushing.

sence of transverse wall reinforcement increases joint strength in connection. The optimum amount of wall reinforcement depends on the strength of grout in the joint. With low-strength grouts, the joint strength is increased substantially by filling the slab cores with grout in the joint region. However, in the case of high-strength grouts, filling the slab cores was only effective if the wall panels were adequately reinforced to prevent splitting.

The following conclusions are based on results of the experimental program:

Joint capacity increases with grout compressive strength, and joint strength is controlled by grout crushing.

Wall splitting does not occur when low-strength grout is used.

For unreinforced walls, as the grout strength approaches wall compressive strength, the mode of joint behavior changes from grout crushing to wall splitting. Therefore, grout strengths higher than wall strengths do not increase joint capacity unless the wall is adequately reinforced. The amount of wall reinforcement required to prevent splitting increases with grout strength.

Filling slab cores with grout directly affects joint strength when low strength grouts are used. However, when medium or high strength grouts are used, filled cores are effective only if the wall panels are reinforced.

Inadequate dry packing below the upper wall panel leads to a substantial loss of joint strength.

Floor moment and rotation do not have a significant effect on joint capacity.

ussed. A new design procedure is proposed. Comparisons of  
calculated strengths for various joint specimens are made.

ion, details of the experimental program and properties of  
oints, are included as appendices to the report.

recommendations for specific analysis and design of connec  
d in Report 5.

"large panel" (LP) concrete structure is used to describe a system composed of precast vertical wall panels with precast floor panels or planks assembled as shown in Fig. 1. These prefabricated buildings can be considered to be the industrialized form of cast-in-place structural wall (egg crate) construction. Buildings are differentiated by the general arrangement of load-carrying walls as shown in Fig. 2:

Cross wall system: in this most prevalent form, load-bearing walls are perpendicular to the longitudinal axis of the building.

Spine wall system: for this form load-bearing walls are parallel to the longitudinal axis of the structure.

Mixed systems: a combination of cross wall and spine wall systems is used.

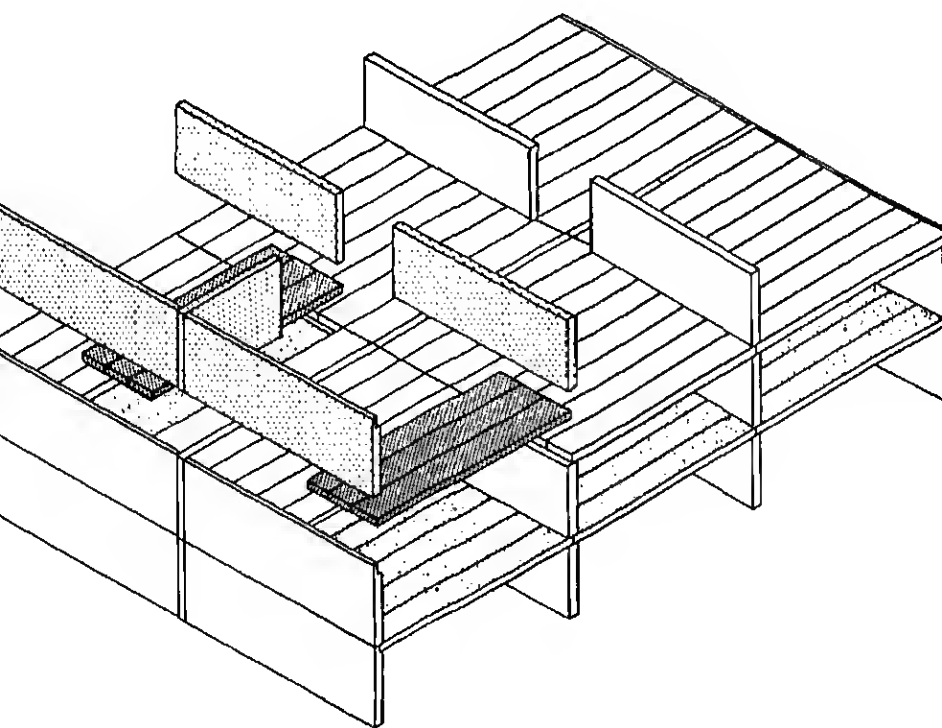
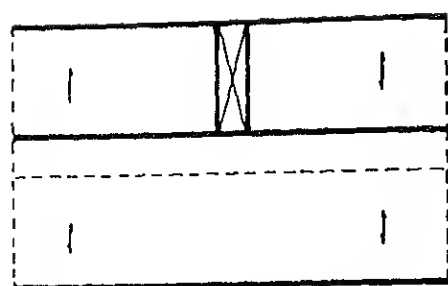
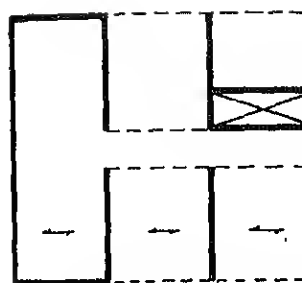


Fig. 1 Isometric View of Idealized Large Panel Structure



(a) Cross Wall System



(b) Spine Wall System

Fig. 2 Idealized Plan Arrangement of Structural Wall Panel Structures

In most LP systems, the walls transfer their loads directly to the structure without an intermediate frame. This form of construction requires plans at any level. Thus it is most typically suited for multistorey buildings where walls have to be provided between apartments to resist fire and sound transmission. Construction types considered under this investigation include solid, sandwich, ribbed, hollow core or composite. Solid, hollow core, or ribbed floor units with or without cast-in-place concrete are also included. All elements can be either prestressed or conventionally reinforced.

The overall program objective is to develop minimum criteria for design and construction of large panel structures. These criteria are developed to ensure structural safety and serviceability of LP residential buildings, while also providing minimum performance requirements to designers and developers of innovative systems. Development of these criteria will also expand the knowledge of design and construction of large panel structures to a level comparable with that existing for conventional in-place concrete or steel structural systems.

structural viewpoint, the essential difference between a cast-in-place concrete structure and a precast large panel structure is the nature of the connections between elements. The function of connections is to transfer loads from one element to another. Ability of large panel structures to perform satisfactorily under all conditions of loading depends upon the quality of the connections. Connections must transmit gravity loads from floors to walls, from wall to wall, and from wall elements to the foundations. They also provide for interaction between the various elements and must provide adequate ductility in resisting lateral loads. If the connections are weak, the strength of the adjoining elements may not be fully utilized.

Connections may be classified <sup>(1)</sup> as interior horizontal wall-to-wall, exterior horizontal wall-to-floor, horizontal floor-to-floor, and horizontal floor-to-wall. The main objective of the tests described in this report is to investigate behavior of wall-to-floor connections commonly used in multi-story buildings in the United States. The report covers tests of both interior and exterior wall-to-floor joints. A single configuration of "Platform Joints" was used in all tests. The compressive strength of concrete in wall panels and hollow-core slabs was determined. The strength of dry-packed mortar below the upper wall panel was also determined. The results of the test series.

The results of the static analysis and design techniques for types of connections used in LP structures, are presented in Report 5 <sup>(2)</sup>.



Details of the test specimens for interior and exterior joints are shown in Figs. 3 and 4, respectively. Controlled variables included in the test program were:

- (a) strength of grout in the joint,
- (b) amount of transverse reinforcement at the top and bottom of the panels,
- (c) filled or unfilled slab cores, and
- (d) applied floor moment and rotation.

Design compressive strength of concrete used in the wall and floor precast floor slab elements was about 5000 psi (34.5 MPa).

## 2.1 Test Specimens

Sixteen full-scale wall-to-floor connections and seven splitting tension specimens were tested. In the connection test specimens, the floor elements consisted of precast concrete hollow-core slabs and the wall elements were blocks of precast concrete. Nominal thicknesses of floor planks were 8 in. (203 mm) and 24 in. (610 mm), and

Detailed descriptions of materials, specimen fabrication, and test procedures are given in Appendix C.

### 2.1.1 Specimen JM-1

Before beginning the main test program, Specimen JM-1 was tested to determine the influence of applied floor moment and rotation on joint strength. The test was performed using two long slabs on each side of the connection. Test set-up and loading arrangement are shown in Fig. 5. Vertical load was applied to the wall in increments by a hydraulic testing machine. Three rams<sup>(3)</sup> were used to apply floor moment by applying

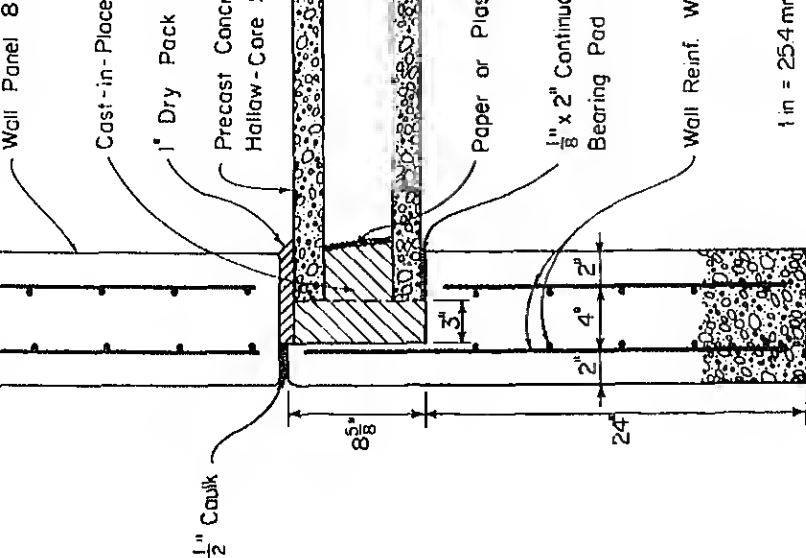


Fig. 3 Interior Joint Specimen

Fig. 4 Exterior Joint Specimen

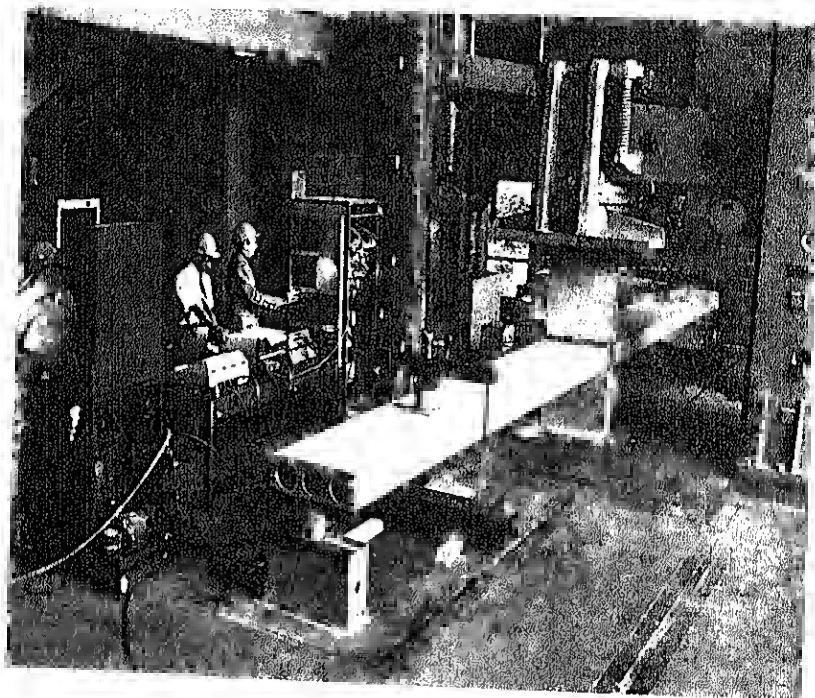


Fig. 5 Test Setup for Specimen JM-1

s(4).

tive moment introduced at the joint was slightly less than the calculated cracking moment for a 24-in. (0.61 m) wide unreinforced slab. Each floor load was positioned at about the third point from the simply supported end of the slab. This provided a moment-to-cracking moment ratio of about 5 at the joint. The figure was based on calculations for a 30-ft. (9.14 m) long slab, assumed fixed at both ends.

Specimen JM-1, grout strength was 3000 psi (20.7 MPa). The top and bottom walls were unreinforced.

## 2 Series A - Splitting Tests

Splitting tests were performed to determine the optimum amount of transverse reinforcement needed in the ends of the walls to prevent splitting. Wall blocks were plastered to the base of the test machine. Vertical load was applied on top through a 3-in. (76 mm) by 24-in. (610 mm) long steel plate. This loading area corresponded to the area loaded by the grout column in a compression test. Figure 6 shows the test setup for this series. Compression strength and amount of reinforcement provided for specimens in this series are shown in Table 1.

## 3 Series J and B - Interior Joint Tests

Tests were conducted in Series J and B. Figure 7 shows the results. A comparison of test results from trial Specimens JM-1 and JM-2 indicated that applied floor moment and rotation did not reduce the joint strength. Consequently, short slabs, without any applied floor moment, were used for the remaining tests. However, the slabs were supported at the free ends to prevent rotation.

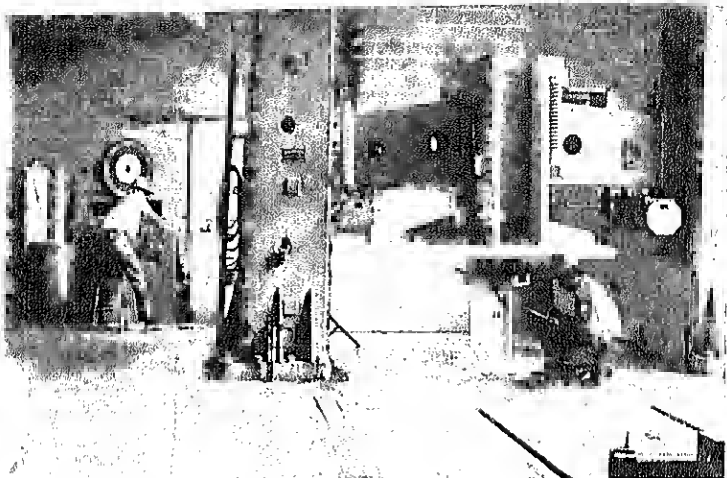


Fig. 6 Splitting Wall Test Setup

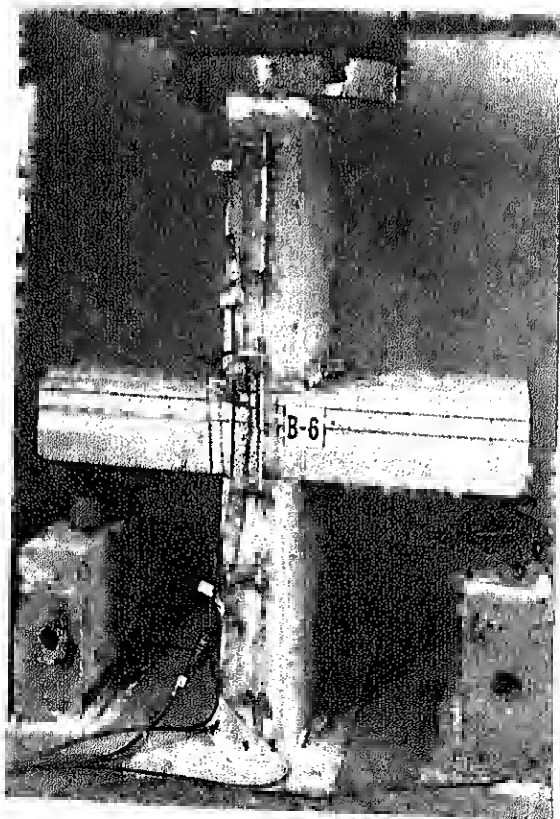


Fig. 7 Interior Joint Test Setup

Specimen Number	Concrete Strength* (psi)	Amount of Wall Reinforcement (in. <sup>2</sup> )	Size of Welded Wire Fabric**
A-1	5040	0	0
A-2	4910	0.041	6x6 - W2.1xW2.1
A-7	5040	0.082	6x6 - W2.1xW2.1
A-3	5040	0.116	6x6 - W2.9xW2.9
A-4	4910	0.144	6x6 - W2.1xW2.1
A-5	4910	0.227	6x6 - W2.1xW2.1
A-6	4910	0.309	6x6 - W2.1xW2.1

\*Average compressive strength measured on six 6x12-in. cylinders.

\*\*6x6-in. mesh with W2.1 and W2.9 wires corresponds to diameters of 0.162 and 0.192 in., respectively.

Metric equivalents: 1 psi = 6.89 kPa  
1 in. = 25.4 mm

Controlled test variables were:

- (a) strength of grout in the joint,
- (b) amount of transverse wall reinforcement, and
- (c) filled or unfilled slab cores.

Grout strength, amount of wall reinforcement and other details of the different interior joint tests are given in Table 2.

#### 2.1.4 Series E - Exterior Joint Tests

Details of exterior joint test specimens are shown in Figure 7. In the full-scale tests were conducted. Controlled variables in the test program were similar to those for interior joints. The test setup is illustrated in Fig. 8. The layout of the test setup was similar to the interior joints.

Grout strength, amount of wall reinforcement and other details of the exterior joints are given in Table 3.

Wall Panel Concrete Strength* (psi)	Grout Strength* (psi)	Amount of Wall Reinf.** (in. <sup>2</sup> )	Slab Cores Filled or Unfilled	
4860	3000	0	Filled	Po Dr
4860	3000	0	Filled	
5380	2730	0	Unfilled	
5380	3240	0.116	Unfilled	
5420	2980	0	Filled	
5310	3260	0.116	Filled	
4810	4510	0.116	Unfilled	
4820	5000	0	Filled	
4820	5000	0.116	Filled	
5310	6800	0.116	Filled	
4810	4510	0.116	Filled	

compressive strength measured on nine 6x12-in. cylinders.

9xw2.9, four cross wires per wall,  $A_s = 4 \times 0.029 = 0.116$  in.

n with long slabs and applied floor moment.

Equivalents: 1 psi = 6.89 kPa.  
1 in = 25.4 mm

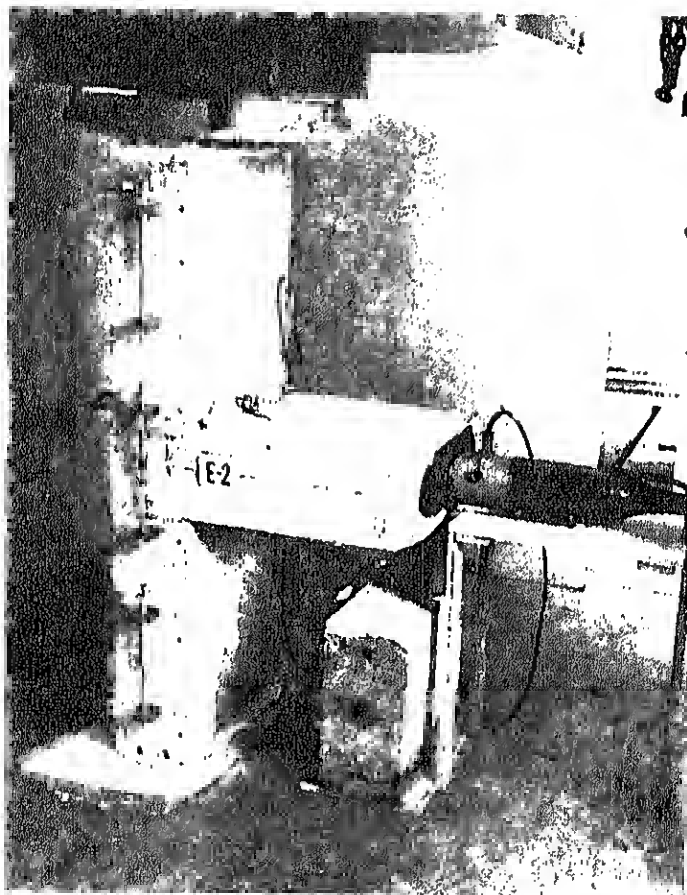


Fig. 8 Exterior Joint Test Setup



Specimen Number	Wall Panels Concrete Strength* (psi)	Grout Strength* (psi)	Amount of Wall Reinf.** (in. <sup>2</sup> )	
E-1	5420	2980	0	
E-2	5180	2840	0	
E-3	5180	4770	0	
E-4	4900	4630	0	
E-5	4900	4510	0.116	

\*Average compressive strength measured on six 6x12-in. cyl

\*\*6x6-W2.9xW2.9, four cross wires per wall panel,  $A_s = 4 \times 0.$

Metric Equivalents: 1 psi = 6.89 kPa  
1 in. = 25.4 mm

### Specimen Strength

red ultimate loads and relevant data are listed in Table .  
nience, these results are expressed both as ultimate l  
as average wall stress. The latter was obtained by divi  
ate load by the bearing area of the wall panel. Also  
4 are the behavior observations at ultimate load. T  
ssed further in Section 3.3.

red values of the ultimate load versus wall reinforcement  
ting test series are shown in Fig. 9. The minimum amount  
ment to give slightly higher ultimate load in splitting t  
mined as  $0.116 \text{ in.}^2$  ( $75 \text{ mm}^2$ ). This reinforcement wa  
cient to limit wall splitting in the subsequent joint te  
o medium strength grouts were used.

### Joint Shortening

tion of vertical shortening, top wall horizontal strain, a  
l crack widths with applied loads for Specimen J-2 are  
10, 11, and 12, respectively. Average vertical strain f  
all panels was calculated by dividing the total shortening  
using LVDT's<sup>(3)</sup> by the 10 in. (254 mm) gage length. P  
tests showed similar trends.

shortening is due to compression of the grout column and t  
end of each of the floor slabs. Grout strength had a major  
on the amount of shortening. Overall shortening was gre  
strength grouts. For similar conditions of grout strength  
orcement, joint shortening in specimens with unfilled sl  
at least 33% higher than those with cores filled. Transver  
orcement reduced measured wall shortening. This was prob  
creased splitting in reinforced wall panels.

Specimen Number	Ultimate Load $P_u$ (kips)	Average Wall Stress** (psi)	Wall Panel Concrete Strength (psi)	Grout Strength (psi)	Slab Cores Filled or Unfilled	Observations at Ultimate Load	Remarks
JM-1 J-1	350 300	1820 1560	4860 4860	3000 3000	Filled Filled	Wall Splitting <sup>+</sup> Wall Splitting <sup>+</sup>	Poor Dry Packing (inadequately packed)
B-6	343	1790	5380	2730	Unfilled	Grout Crushing	--
B-7*	360	1870	5380	3240	Unfilled	Grout Crushing	--
B-5	440	2290	5420	2980	Filled	Grout Crushing & Wall Splitting	Both Upper & Lower Walls Split
B-2*	460	2400	5310	3260	Filled	Grout Crushing	--
B-3A*	440	2290	4810	4510	Unfilled	Grout Crushing	--
J-2	465	2420	4820	5000	Filled	Wall Splitting <sup>+</sup>	--
J-3*	520	2710	4820	5000	Filled	Grout Crushing	--
B-4*	525	2730	5310	6800	Filled	Lower Wall Splitting	Upper Wall & Grout Uncracked
B-1*	266	1380	4810	4510	Filled	Slab Crushing	No Grout Column, Slab Cores Filled

\*Wall Panels reinforced with 6x6 - W 2.9 X W 2.9,  $A_s = 0.116$  in. 2

\*\*Average wall stress obtained by dividing ultimate load by gross wall area

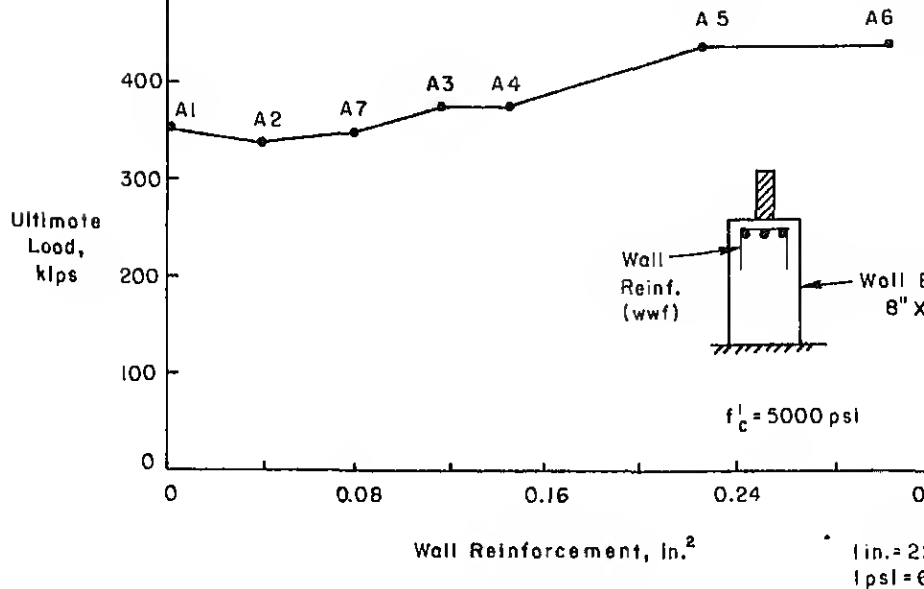


Fig. 9 Splitting Tests - Series A

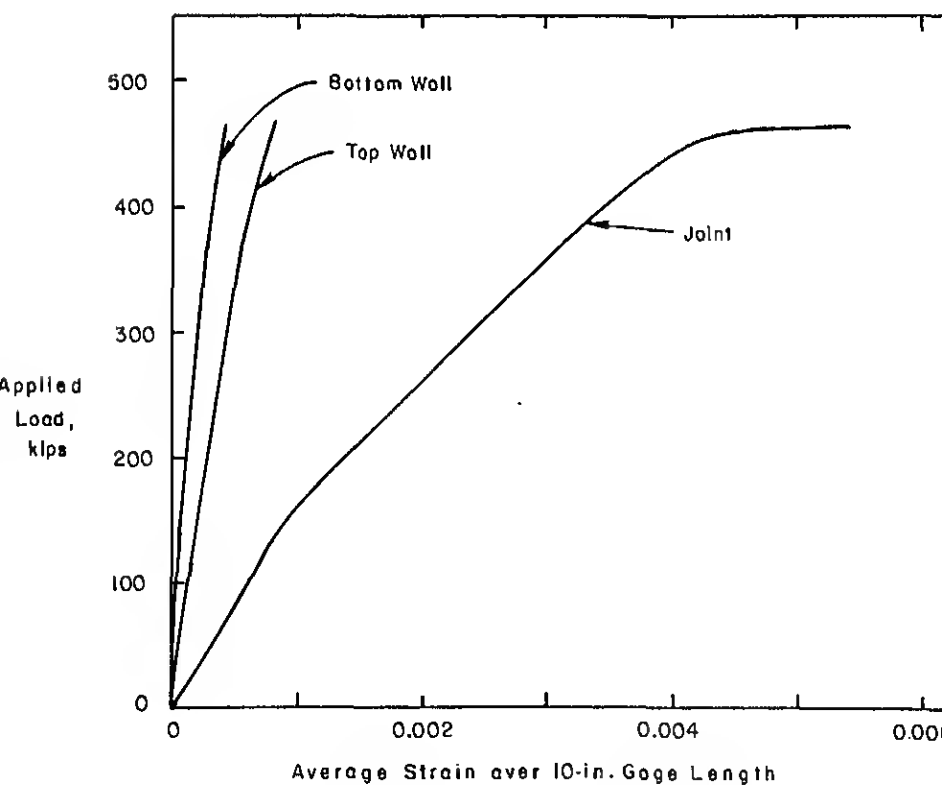


Fig. 10 Load versus Shortening for Specimen A

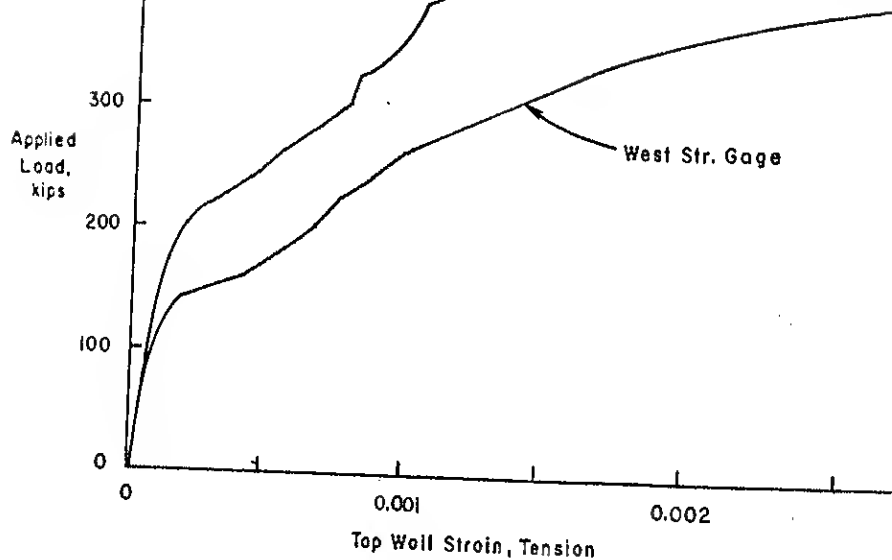


Fig. 11 Load versus Top Wall Strain for Specimen J-2

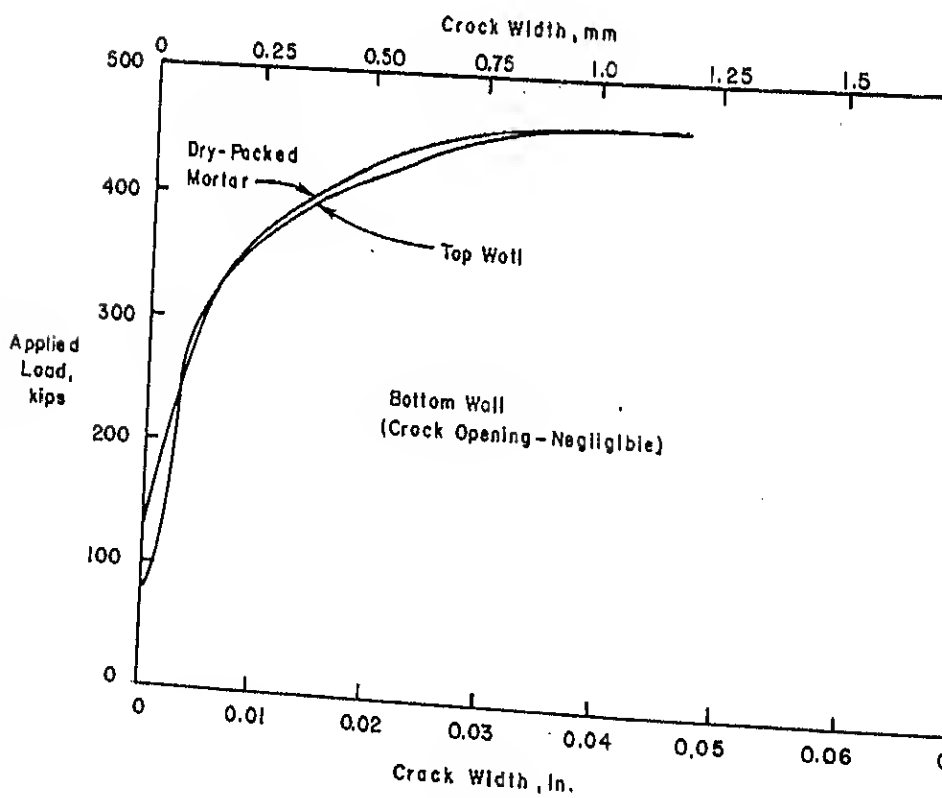


Fig. 12 Load versus Wall Separation for Specimen J-2

load can pass through an interior joint from the upper wall to the lower wall in either of two distinct fashions.

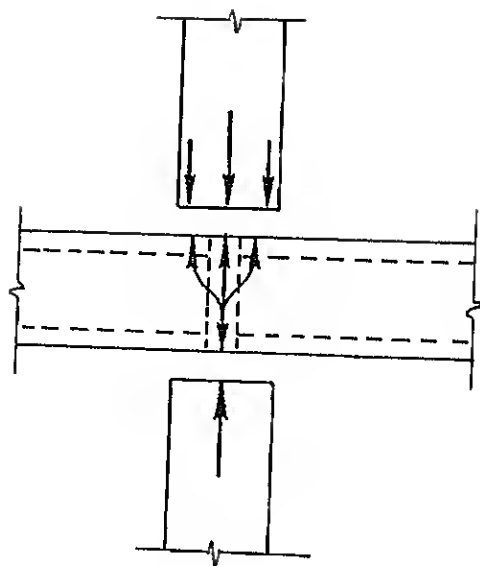
In the first case shown schematically in Fig. 13(a), the joint functions in a monolithic fashion. Stresses across the top of the joint are generally uniform. However, due to soft bearing pads beneath the slab, the load is funnelled into the bottom of the grout column causing a stress concentration in the lower portion of the joint as shown. Stresses are transferred at the slab-grout column interface.

In the second case, shown schematically in Fig. 13(b), the joint consists of three distinct vertical "columns": a grout column in the center and concrete columns on either side. The outer columns consist of the slab and bearing pads. The amount of load that each "column" supports is determined by the stiffness of that column in relation to the other columns. Uniform material properties produce generally uniform stress distributions across the joint, while greatly differing properties cause stress concentrations.

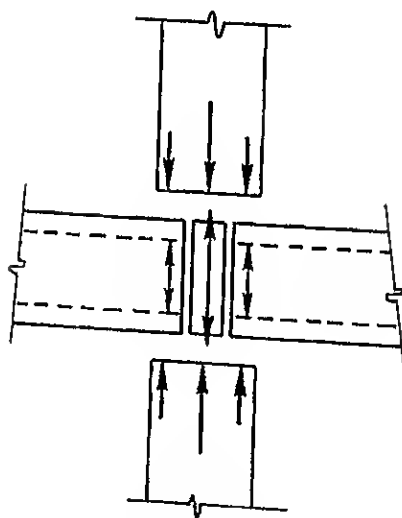
For a particular interior joint, load flow patterns and behavior are determined by four variables:

1. Compressive strength of the grout as related to the compressive strength of the wall and slab concrete is one variable. For purposes of discussion, "low", "medium", and "high" strength grouts are defined as having compressive strengths, respectively, less than, equal to and greater than the compressive strength of the slab and wall concrete. The slab and wall concrete are assumed to have equal strength.

2. Extension of the grout into the hollow cores of the slab is another variable. Hollow cores are considered filled if the grout extends at least to the plane of the face of the wall.



(a) Before Cracking



(b) After Cracking

Fig. 13 General Behavior - Interior Joints

verse welded wire fabric as shown in Fig. 3.

Stress level in the joint is a fourth variable.

ects of these variables are discussed in the following sect

### 3.1 Case 1: Low Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

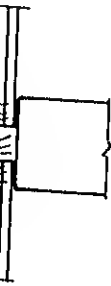
For Case 1 shown in Fig. 14(a) load flow is through discrete columns. Since the slab cores are unfilled and the slab panels are supported on soft bearing pads, the grout column is independent of the slab and carries most of the load. With grout strength less than the wall strength, increasing load produces grout column crushing, identified as Stage 1. With the loss of the grout column, load is transferred to the two slab ends. At their lower net area these eventually crush before damaging the walls. This is identified as Stage 2. Since the capacity of the grout column is generally greater than that of the combined slab ends, maximum capacity is reached at Stage 1.

Stresses in the wall panels never control. Consequently, the behavior and capacity of this joint configuration are not a function of wall reinforcing. This behavior was observed in Specimens B-5 and B-7. Specimen B-6 after testing is shown in Fig. 15(a).

### 3.2 Case 2: Low Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

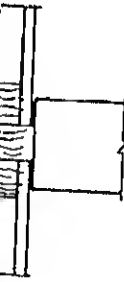
For Case 2 with filled cores as shown in Fig. 14(b), the joint behaves initially as a monolithic element. The funnelling of load is accomplished through shear between the grout column and the slab cores. Vertical stress is initially uniform at the





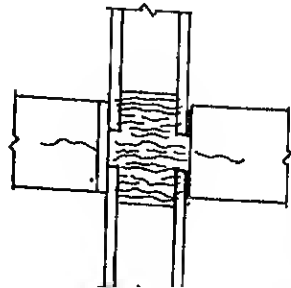
(a) Low strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

- \*1 - Grout Crushes
- 2 - Slab Ends Crush

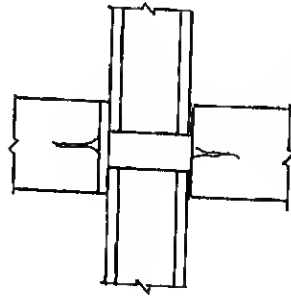


(b) Low Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

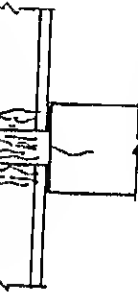
- 1 - Grout Cores Shear Off
- \*2 - Grout Crushes
- 3 - Slab Ends Crush



(e) Medium Strength Grout, Cores Filled, Walls Reinforced

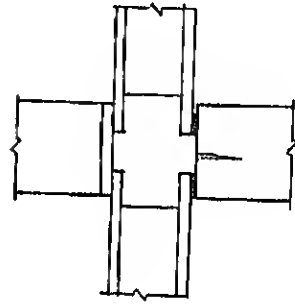


(f) High Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced



(c) Medium Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

- 1 - Both Walls Crack
- \*2 - Grout Crushes
- 3 - Slab Ends Crush

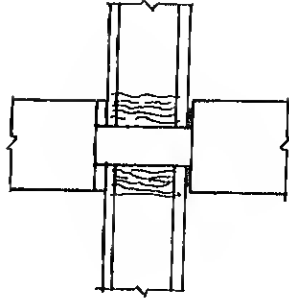


(g) High Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

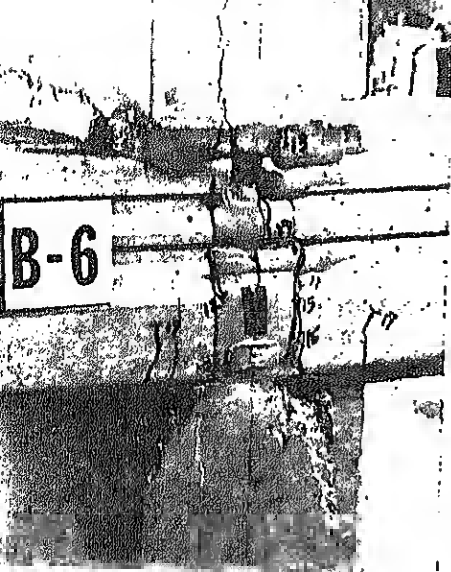


(d) Medium Strength Grout, Cores Filled, Walls Unreinforced

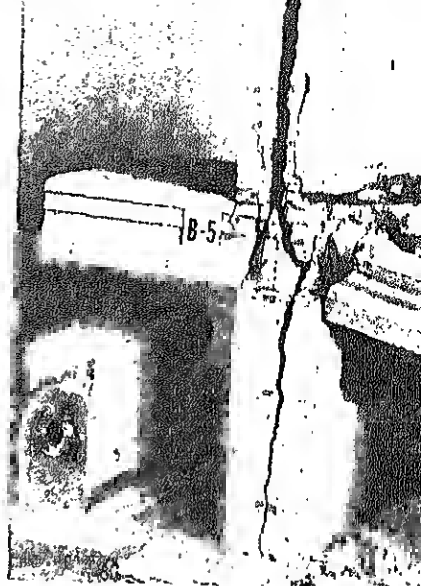
- 1 - Grout Cores Shear Off
- 2 - Both Walls Crack
- \*3 - Upper Wall Splits



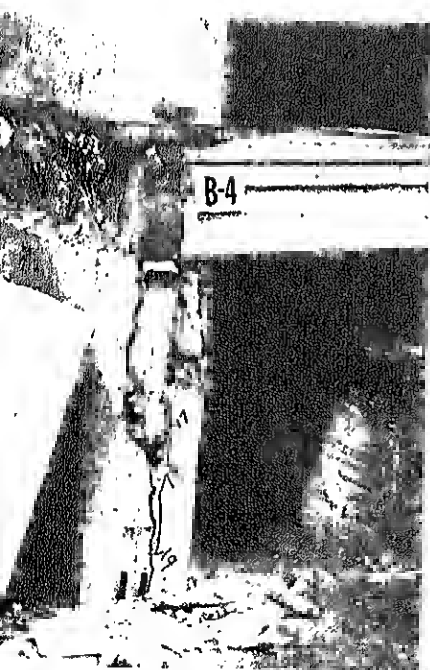
(h) No Grout in Joint, Walls Reinforced or Unreinforced



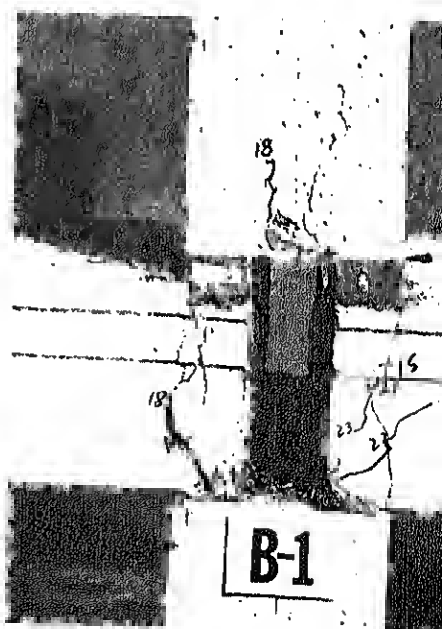
Grout Crushing



(b) Upper Wall Splitting



(c) Lower Wall Splitting



(d) Slab Crushing

grout column. This is identified as Stage 1.

Following Load Stage 1, the load flow is through the columns. Due to the soft bearing pads under the grout column carries most of the load. With grout strength less than wall strength, increased load produces failure identified as Stage 2, and load is transferred to the slab ends. Although the slab ends have additional strength due to the grout cores, they are still weaker than the wall element. The final stage of failure of the slab ends is the final stage. This type of failure is evident in Specimens B-2 and B-5. Secondary splitting failure also occurred in Specimen B-5, shown in Fig. 15(b). When the maximum joint capacity is reached when grout failure occurs at Stage 2. Stresses in the wall panels never reach their capacity, consequently reinforcing does not affect behavior of the joint in this joint configuration.

### 3.3.3 Case 3: Medium Strength Grout, Cores Unfilled and Reinforced or Unreinforced

For Case 3 shown in Fig. 14(c), load flow is through the columns and vertical columns. The soft bearing pads and unfilled grout under the slab ends cause the grout column to support most of the load. This leads to vertical stress concentrations at the wall-grout interface, which produces horizontal tensile stresses in the walls. As the load increases, it cracks the upper and lower walls, identified as Stage 1. With an increase in load, however, causes grout crushing between the walls and splits. This is identified as Stage 2. Grout crushing occurs due to load transfer to the slab ends and eventual slab failure. This is identified as Stage 3. The capacity of the grout column is less than that of the combined slab ends. As a result, failure occurs at the grout column reached at Load Stage 2.

behavior and capacity of the joint are not expected to be changed by reinforcing. Specimen B-3A containing reinforcement exhibited similar behavior.

#### 4 Case 4: Medium Strength Grout, Cores Filled, Walls Unreinforced

Case 4 shown in Fig. 14(d), grouted cores cause the joint to behave initially as a monolithic element. Vertical stresses are uniform at the top of the joint and concentrated in the grout column at the bottom of the joint. As load is increased, the capacity of the medium strength grout cores is reached and the grout cores are sheared off from the grout column. This behavior is identified as Stage 1.

Following Stage 1, load flow is through discrete vertical columns. The grout column carries most of the load, but not as much as in Case 3. This is due to the increased stiffness of the grouted cores versus the ungrouted cores in Case 3. The vertical stress concentrations at the wall ends caused by the grout column increase the compressive stresses in the walls. Increased load causes cracking of the upper and lower walls. This is identified as Stage 2.

Under the same total vertical wall load, the grout column in this case carries a slightly lower stress than in Case 3. The difference is enough to split the unreinforced walls, identified as Stage 3. This behavior was observed in Specimen J-2, where the upper wall split.

#### 5 Case 5: Medium Strength Grout, Cores Filled, Walls Reinforced

The joint configuration, shown in Fig. 14(e), is identical to Case 4 with the exception of the addition of transverse steel reinforcing in both upper and lower wall panels. Behavior is identical to that of Case 4 through Load Stage 2. As the load

the slab ends which also eventually crush. This is identified as Stage 4. The capacity of the grout column confined between the slab ends, is generally higher than that of the combined grout column and slab ends. Therefore, ultimate capacity is reached when grout column crushes at Stage 3. This behavior was observed in Specimen J-3.

#### 6 Case 6: High Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

Case 6 shown in Fig. 14(f), no specimen was tested. However, based on observations from the other tests, the behavior can be anticipated. Load flow is through discrete vertical columns. The bearing pads and unfilled cores of the slab ends cause the grout column to support most of the load. The grout column has higher strength than the wall. Consequently, horizontal tensile stresses in the walls, due to the vertical stress concentration, will become critical long before the grout column capacity is reached. Increased load first cracks the upper and lower walls and then splits them. This is identified as Stages 1 and 2 respectively. Splitting will occur whether or not the walls are externally reinforced.

#### 7 Case 7: High Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

Case 7 shown in Fig. 14(g), The grouted cores cause the walls to respond as a monolithic element. Vertical stress is uniform above the top of the joint and concentrated in the grout column above the bottom of the joint. Under increasing load, the grout cores come off the grout column because of the increased shear capacity of the high strength grout. Instead, the vertical stress concentration at the bottom of the joint causes horizontal tensile stresses to develop in the lower wall. These latter stresses become critical

ntified as Stages 1 and 2, respectively. Splitting will  
ther or not the walls are nominally reinforced. This bel  
observed in Specimen B-4, shown in Fig. 15(c).

#### 8 Case 8: No Grout in the Joint, Walls Reinforced or Unreinforced

e 8, shown in Fig. 14(h), represents an extreme limit of C  
d flow is solely through the outside slab ends. Capacity o  
nt is reached as the slab ends crush, identified as Sta  
esses in the wall panel never become critical, consequently  
avior and capacity of the joint are not altered by reinfor  
s behavior was observed in Specimen B-1, shown in Fig. 15(d)

#### Effect of Variables on Joint Strength

cts of variables on interior joint strength may be summariz

A change in a variable to cause a more uniform ver  
compressive stress across the width of the joint gene  
increases the vertical load-bearing capacity of the joint.

Under certain circumstances, control of vertical cracki  
walls increases the vertical load carrying capacity o  
joint.

the variables examined, a list of interior joint configura  
in Table 5. The purpose of the table is to list the joint  
ons in ascending order of capacity. Behavior of joint conf  
at were not tested have been estimated.

TABLE 5 - INTERIOR JOINT CONFIGURATION IN  
ASCENDING ORDER OF CAPACITY

Specimen	Joint Configuration	Strength of Grout	Cores Filled	Walls Reinforced	Behavioral Case	Behavior at Ultimate
B-1	JC1	No Grout	No	Either	8	Slab End Crushing
B-6, B-7	JC2	Low	No	Either	1	Grout Crushing
B-2, B-5	JC3	Low	Yes	Either	2	Grout Crushing
B-3a	JC4	Medium	No	Either	3	Grout Crushing
-	JC5*	High	No	No	6	Wall Splitting
J-2	JC6	Medium	Yes	No	4	Wall Splitting
-	JC7*	High	No	Yes	6	Wall Splitting
-	JC8*	High	Yes	No	7	Wall Splitting
J-3	JC9	Medium	Yes	Yes	5	Grout Crushing
B-4	JC10	High	Yes	Yes <sup>4</sup>	7	Wall Splitting

\*Rank estimated based on test results for other specimens.

strength ranging from about 2700 psi to 6800 psi (18.6 MPa) had a significant effect on joint strength. Measured ultimate loads versus grout strengths for test specimens are shown in Fig. 16. It can be seen that joint strength generally increased with grout strength, provided the capacity was controlled by grout crushing. However, as indicated in Table 5, for joint configuration JC10, high strength grout alone did not ensure greater capacity. As shown in Fig. 16 for Specimen B-4, joint strength was controlled by wall splitting, and grout strength was never reached.

## 2 Transverse Wall Reinforcement

Transverse wall reinforcing reinforcement had no effect on strength in joint configurations JC1 through JC4. In these configurations, joint strengths were controlled by grout crushing. This is shown in Fig. 16 for the four joint configurations of Table 5. Reinforcement increased joint capacity when the strength was controlled by wall splitting. For unreinforced wall. This corresponds to joint configuration JC9 and was observed in Specimens J-2 and J-3.

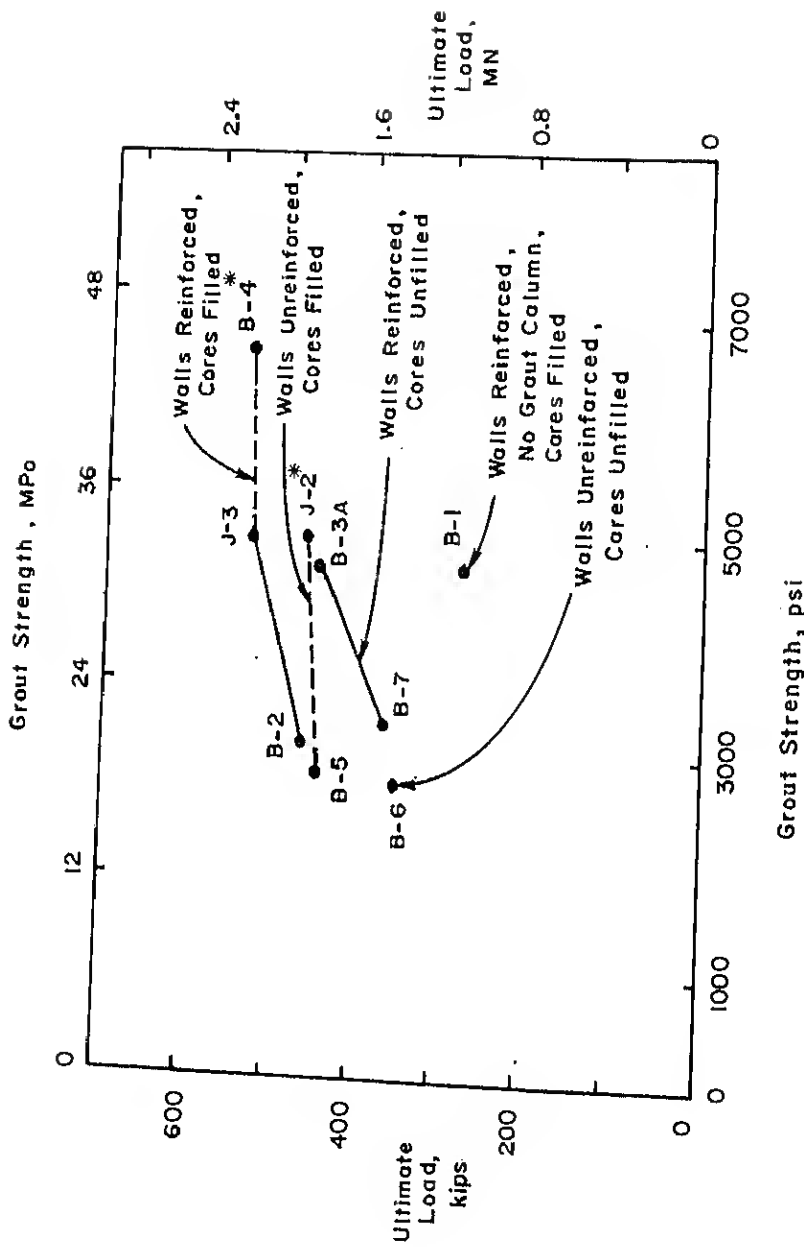
## 3 Filled Slab Cores

Under similar conditions of grout strength and wall reinforcement, filled cores in the connection region increased joint capacity. Filled cores increased the stiffness of the slab ends thereby resulting in a more uniform vertical stress distribution in the joint. Consequently, crushing of the grout occurred at higher loads.

## 4 Applied Floor Moment and Rotation

Various loading conditions were used to determine the influence of moment and rotation on joint strength. The intensity of the applied floor load was such that the negative moment introduced





of about 5 at the joint. The results indicate that  
tension and rotation do not affect joint strength significantly.  
tension does induce some tensile splitting forces into the  
1. However, the effect is minimal and generally can be  
neglected.

## 2.5 Dry Packing

In addition to the variables discussed above, joint performance is  
influenced significantly by the uniformity of dry-packed mortar  
below the upper wall panel. Well-packed mortar leads to uniform  
stresses below the upper wall. Poor dry packing leads to nonuniform  
stresses, thereby substantially reducing joint strength due to  
premature splitting of the upper wall.

## Experimental Determination of "Stiffness Factor"

The compressive load applied to the upper wall panel is transferred  
to the lower wall panel through the grout column between the floor  
slabs supported on the bearing pads. A greater part of the load  
, however, takes place through the grout column. The percentage  
transferred through different elements in a horizontal joint depends  
on the relative stiffness of each element in relation to the  
stiffness of the connection. Stress flow in the slabs is uniform  
across the slab depth and in the direction of the floor joists.  
Therefore, the effective plank stiffness is indeterminate and depends  
on material properties, load pattern, and geometry of connection.  
It is considered based on measurements made on joint shortening  
at column shortening.

## 3.1 Joint Shortening

Joint shortening was measured over a height of about 10.6  
in. (270 mm). This distance included grout column, dry pack, and  
1 in. (25 mm) each of top and bottom walls.

sely represents conditions in the joint after vertical cracking takes place at the end of each floor element separating the grout column from the grout in the slab cores. Each discrete column is considered to act independently.

Using the notation given in Fig. 17(a),

$$\sigma = \frac{\delta l_1}{l_1} E_1 = \frac{\delta l_2}{l_2} E_2 = \frac{\delta l_3}{l_3} E_3 = \frac{\delta l_4}{l_4} E_4 \quad (\text{Eq. B-1})$$

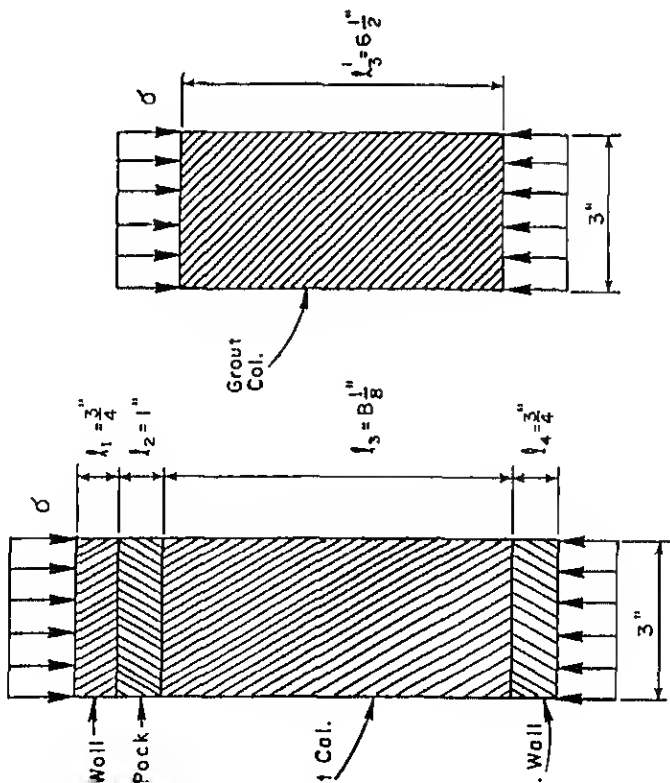
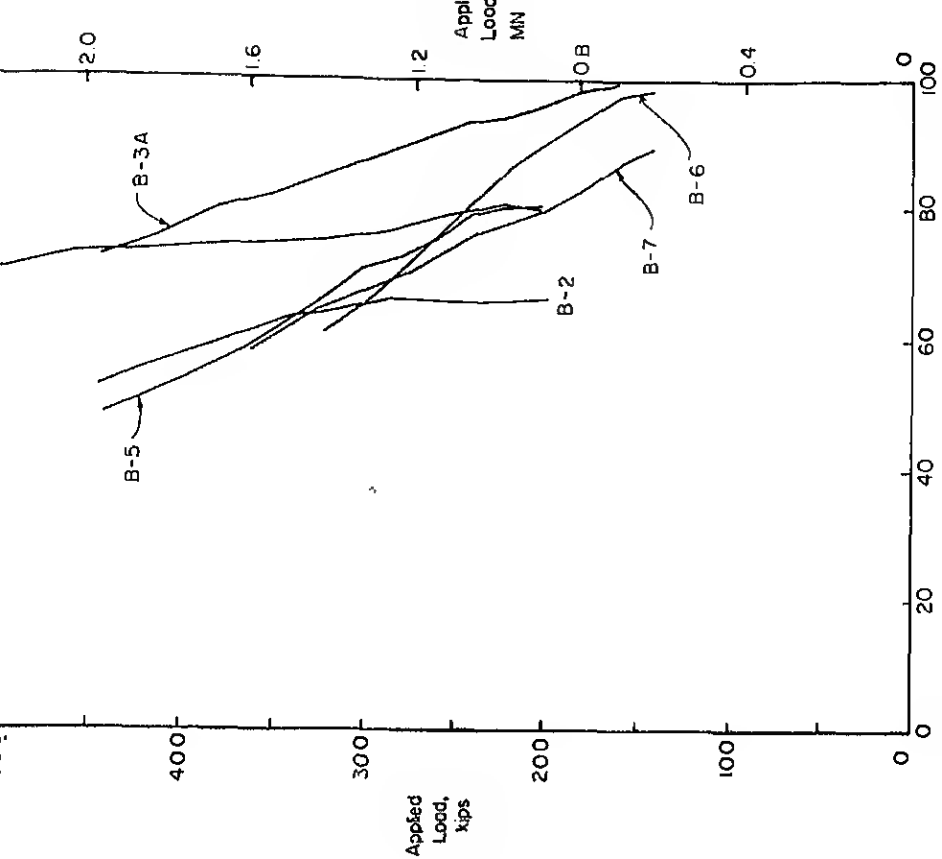
$$\begin{aligned} \delta l_3 &= \delta l - \delta l_1 - \delta l_2 - \delta l_4 \\ &= \delta l - \sigma \left( \frac{l_1}{E_1} + \frac{l_2}{E_2} + \frac{l_4}{E_4} \right) \end{aligned} \quad (\text{Eq. B-2})$$

where  $\sigma$  = uniform vertical stress in column,  
 $\delta l_1, \delta l_2, \delta l_3, \delta l_4$  = shortening over heights  $l_1, l_2, l_3, l_4$  of Elements 1, 2, 3, 4, respectively,  
 $\delta l$  = measured joint shortening =  $\delta l_1 + \delta l_2 + \delta l_3 + \delta l_4$ , and  
 $E_1, E_2, E_3, E_4$  = modulus of elasticity of Elements 1, 2, 3, 4, respectively.

The shortening in grout column,  $\delta l_3$ , was determined from the above expression by assuming a uniform vertical stress,  $\sigma$ , and using corresponding values of  $E_1, E_2$  and  $E_4$  from a family of stress-strain curves plotted for materials of different compressive strengths. A trial and error method was used to match the assumed vertical stress with the grout column stress corresponding to the measured grout column shortening  $\delta l_3$ .

Therefore, the amount of load transferred through the grout column is given by:

$$P_g = \frac{\delta l_3}{l_3} (E_3) (A_g) \quad (\text{Eq. B-3})$$



(a) Joint Shortening

(b) Grout Column Shortening

### 3.5.2 Grout Column Shortening

Stress analysis based on total joint shortening described in Section 3.5.1 was quite complex. It involved materials with different elastic properties. The voids left between different materials as a result of construction procedures and subsequent shrinkage were not considered in the analysis. This resulted in a high calculated percentage of load transferred through the grout column in the initial load stages.

Shortening in the grout column alone was also measured in Specimens 8-6 and 8-7. Strain measurements were taken over a height of about 6.3 in. (160 mm).

Assuming a uniform stress throughout the length of the grout column as shown in Fig. 17(b), the percentage of applied load transferred through the grout column was calculated.

$$\sigma = \frac{\delta l'_3}{l'_3} E_3 \quad (\text{Eq. 6})$$

where  $\delta l'_3$  = shortening over height  $l'_3$  of grout column

Therefore, the amount of load transferred through the grout column is given by:

$$P_g = \frac{\delta l'_3}{l'_3} (E_3) (A_g) \quad (\text{Eq. 7})$$

Using the procedure described in Sections 3.5.1 and 3.5.2, the percentage of load transferred through the grout column was calculated.

ized column by cracking at the slab end and grout column face. Results for Specimens J-3 and B-4 are not plotted due to inconsistent data. Figure 18 shows that the percentage of load transferred through the grout column decreased as the load on the column increased.

ultimate test loads are given in Table 6. For convenience, these results are expressed both as ultimate load,  $P_u$ , and as average wall stress. The latter was obtained by dividing the ultimate load by the bearing area of the wall panel. Also given in Table 6 are the observation of the ultimate load indicating that crushing of the grout occurred in some specimens.

### General Behavior

In interior joints, vertical load can pass through an exterior joint in either of two fashions. In the case shown schematically in Fig. 19(a), the joint functions in a monolithic manner. Load is distributed across the top, nonuniformly due to the built-in eccentricity of the joint. At the bottom of the joint, load is funnelled into the grout column due to the soft bearing pads beneath the ends of the slabs.

In the case shown in Fig. 19(b), the joint consists of two discrete vertical "columns": a grout column in the center and a column on one side consisting of the end of the slab. The load that each "column" supports is determined by the total stiffness of that column and the eccentricity of the joint. As there exists a significant built-in eccentricity because of the discrete slab end on only one side, nonuniform material properties will not produce uniform stresses across the joint, as in the case of interior joints.

In a particular exterior joint, both load flow patterns and behavior are governed by the same four variables as interior joints described in Section 3.3. However, in exterior joints the effects are much less pronounced. As noted above, the basic configuration of the joint leads to nonuniform stresses no matter what the material properties may be. As shown schematically in Fig. 19(c), the joint initially tends to transfer a portion of the load to the centrally located grout column. Consequently,

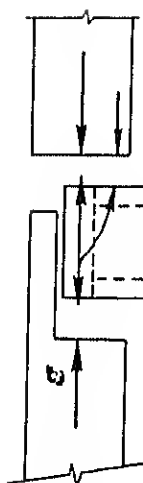
TABLE 6 - TEST RESULTS-EXTERIOR JOINTS

Specimen Number	Ultimate Load $P_u$ (kips)	Average Wall Stress** (psi)	Wall Panel Concrete Strength (psi)	Grout Strength (psi)	Slab Cores Filled or Unfilled	Observations at Ultimate Load	Remarks
E-1	300	1560	5420	2980	Filled	Grout Crushing	--
E-2	290	1510	5180	2840	Unfilled	Grout Crushing	--
E-3	280***	1460	5180	4770	Unfilled	Grout Crushing	Poor Dry Packing (inadequately packed)
E-4	380	1980	4900	4630	Filled	Grout Crushing	--
E-5*	400	2080	4900	4510	Filled	Grout Crushing	--

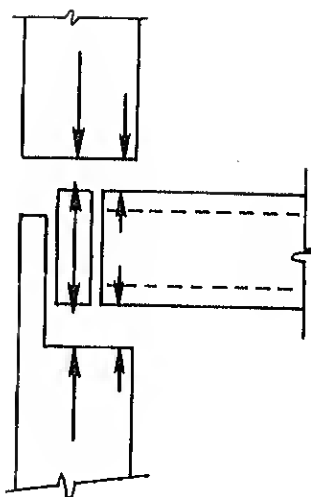
\*Wall Panels reinforced with 6x6 - W 2.9 X W 2.9,  $A_s = 0.116$  in.<sup>2</sup>

\*\*Average wall stress obtained by dividing the ultimate load by the bearing area of wall panel (bearing area is 24x8 in.)

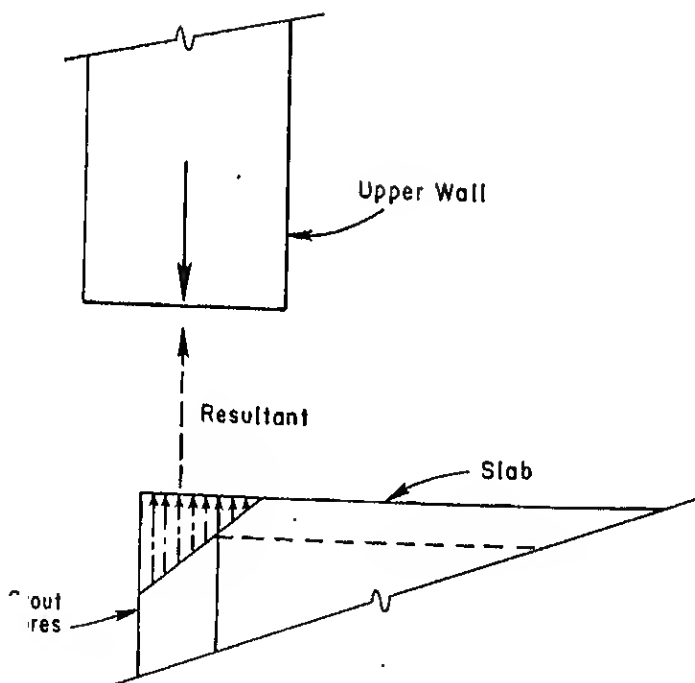




a) Before Cracking



(b) After Cracking



c) Nonuniform Stresses Prior to Ultimate load

General Behavior - Exterior Joints

then compared to similar interior joints.

#### 1.1 Case 1: Low and Medium Strength Grout, Cores Filled or Unfilled, Walls Reinforced or Unreinforced

Case 1, shown in Fig. 20(a), load flow is through discrete columns when cores are unfilled, and through a monolithic slab when cores are filled. In the latter cases, however, the grout carries most of the load. As load is increased, the grout is crushed before tensile splitting stresses, caused by the vertical stress concentration, become critical in the wall panel. This is identified as Stage 1.

After the loss of the grout column, load is transferred to the walls, which also crush, identified as Stage 2. Since the capacity of the grout column is greater than that of the slab end, maximum load is reached at Stage 1.

Tensile stresses in the wall panel never become critical. Therefore, the behavior and capacity of this joint configuration are not altered by reinforcing. A specimen exhibiting this behavior is shown in Fig. 21. Similar behavior was observed in all specimens at increasing load.

#### 2 Case 2: High Strength Grout, Cores Filled or Unfilled, Walls Reinforced or Unreinforced

Specimens representing Case 2, shown in Fig. 20(b), were tested. The load flow is similar to that of Case 1. Due to the eccentric loading of the wall and to the soft bearing pads beneath the wall, the grout again transfers most of the load. The grout has a higher strength than the wall concrete. Consequently, it is expected that horizontal tensile stresses in the walls, due to vertical stress concentration, would become critical long before the grout column capacity is reached.

a) Low & Medium Strength Grout  
Cores Filled or Unfilled,  
Walls Reinforced or Unrein-  
forced

- \*1 - Grout Crushes
- 2 - Slab Ends Crush

(b) High Strength Grout  
Filled or Unfilled,  
Reinforced or Unrei

- 1 - Both Walls Cra
- \*2 - Both Walls Spl

\*Ultimate Capacity

Fig. 20 Behavior at Successive Load Stages - Exterior Joint



Fig. 21 Damage Pattern at Ultimate Load - Exterior Joints

ly. Splitting would likely occur whether or not the walls are initially reinforced.

## Effects of Variables on Joint Strength

Strength was the only variable in the test program that influenced the behavior of the joint. This occurred because the basic configuration of the joint caused most of the load to be transferred through the joint.

For the variables examined, a list of exterior joint details is given in Table 7. The table lists joint configurations in ascending order of ultimate capacity. Behavior of the last two joint configurations has not been estimated.

### 1.1 Strength of Grout

Grout strength ranging from approximately 2800 psi to 4800 psi (19.3 MPa to 33.1 MPa) had a significant effect on joint strength. Measured ultimate loads versus grout strength are shown in Figure 1. It can be seen that with the exception of Specimen E-3, which was only dry packed, joint strength increased with grout strength.

As suggested in Table 7 for configuration JC13 and JC14, the behavior of joints with high strength grout is expected to be controlled by wall splitting.

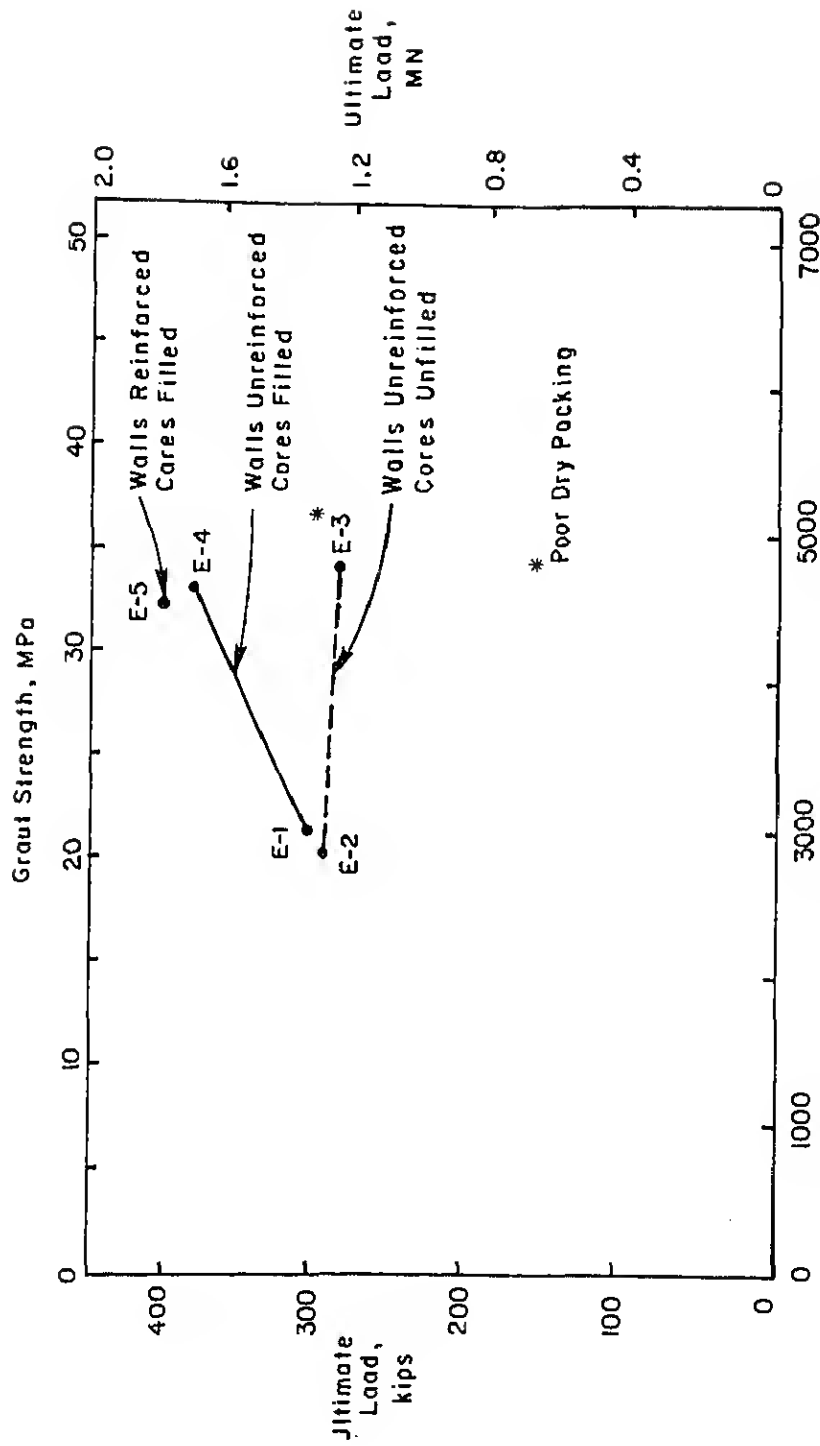
### 1.2 Transverse Wall Reinforcement

Inclusion of split-resisting reinforcement has no effect on joint strength with low or medium strength grout. Reinforcement will increase joint capacity only when the mode of behavior at ultimate is splitting in a non-reinforced wall. Joint configurations JC13 and JC14 would be expected to perform this way.

TABLE 7 - EXTERIOR JOINT CONFIGURATION IN ASCENDING  
ORDER OF CAPACITY

Specimen	Joint Configuration	Strength of Grout	Cores Filled	Walls Reinforced	Behavioral Case	Behavior at Ultimate
E-1, E-2	JC11	Low	Either	Either	1	Grout Crushing
E-3, E-4, E-5	JC12	Medium	Either	Either	1	Grout Crushing
--	JC13*	High	Either	No	2	Wall Splitting
--	JC14*	High	Either	Yes	2	Wall Splitting

\*Rank estimated based on test results for other specimens.



capacity. As the exterior joints have a slab on one side joint only, lesser load is transferred through the slab compared to the interior joints. Therefore, filling the exterior joints will have somewhat less of an effect.

#### 4.3.4 Dry Packing

Poor dry packing can lead to premature joint failure. Dry is more difficult in exterior joints, because mortar has packed from one side of the joint only. Consequently, the ability of inadequate packing is higher.

## Prestressed Concrete Institute Methods

ent years, several methods to determine the load capacity of connections in large panel structures have been proposed. This report discusses three design procedures proposed by the Prestressed Concrete Institute (PCI)<sup>(5)</sup>.

Prestressed Concrete Institute Method 1<sup>(5)</sup> is based on strength of components. Applied design load on the joint is distributed to the components of the joint according to the stress-deformation characteristics of the components. It also allows a "correction factor" on the cylinder strength of concrete or grout in the joint.

Method 1 is empirical in nature, and is complex to use. The method requires experimental data to verify the stress-strain relationships of the components. Elastic properties of the bearing pads used in the tests described in this report differed substantially from those suggested in PCI Method 1.

Prestressed Concrete Institute Method 2<sup>(5)</sup> is based on the strength of a joint. With this approach, the joint is divided into a series of discrete vertical "columns." The amount of load that each "column" supports is a function of the stiffness of that part of the joint. The method permits determination of the stress distribution in the components of the joint under service load conditions. However, the method has the following limitations:

- 1. It underestimates the effective stiffness of a slab by using the width of the "slab column" to the bearing length of the floor slab in calculating areas of discrete vertical "columns." However, analytical investigations<sup>(2)</sup> indicate that additional plank length beyond the edge of a wall participates in transferring vertical load from the upper



2. It does not consider the use of hollow-core slabs and additional stiffness provided by the grout in the slab connection region.
3. It permits determination of stresses in the elastic range, not the load capacity of a joint. Also, the method does not consider the effect of wall reinforcement or the possibility of a splitting failure when high strength grout is used.

Prestressed Concrete Institute Method 3<sup>(5)</sup>, is based mainly on tests conducted by the Danish Structural Research Center. Their load transfer expression seems valid, but is applicable only if grout strength is equal to the joint and the wall concrete strength are similar.

## 5.2 Proposed Design Procedures

### 5.2.1 Interior Joints

Vertical compressive load applied to the upper wall is transferred to the lower wall through the grout column and the wall ends. A greater part of the load is carried by the grout column and slabs carry the rest. Ultimate load,  $P_u$ , can be divided into two parts as follows:

$$P_u = P_g + P_s$$

where

$P_u$  = joint strength

$P_g$  = amount of load transferred through the grout column

$P_s$  = amount of load transferred through the wall slabs

The amount of load transferred through slabs can be increased if the hollow cores are filled. It should be noted, however, that,  $P_u$  does not represent the load capacity of an ungrouted connection.

ed. Strength of an ungrouted connection will, usually, be higher than  $P_s$ . This strength can be determined from the bearing area of slab ends and the compressive strength of slab concrete.

The proposed method limits the maximum useable grout strength and thus, ensures that joint capacity is controlled by grout crushing rather than wall splitting. The maximum useable grout strength, and consequently joint capacity can, however, be increased by selecting proper joint variables, such as grout strength, wall reinforcement, and by filling the slab ends. Therefore, high strength grout can only be used effectively if walls use high strength concrete, they are reinforced against splitting, and the slab cores are filled with grout.

Based on the maximum useable grout strength,  $f_u$ , the following expression for capacity of interior horizontal joints was developed:

$$P_g = K P_u$$

$$P_s = (1 - K)P_u$$

where, basic principles,

$$P_g = t L f_u$$

where  $t$  = width of the grout column - in this case (76 mm),

$L$  = horizontal length of grout column,

$f_u$  = maximum useable strength of grout defined as follows: compressive strength of grout or wall concrete,  $f'_c$ , whichever is less, not more than 4000 psi (27.6 MPa), unless walls are reinforced against splitting and slab cores are filled with grout,

load transferred through the grout was found to increase linearly from a value of 0.65 for a grout strength (17.24 MPa) to a value depending of grout in the joint,  $f_g$ .

For simplicity, K can be taken as follows:

$$\begin{aligned} K &= 0.65 + \left[ \frac{f_g - 2500}{50,000} \right] \text{ for } f_g \text{ in psi,} \\ &= 0.65 + \left[ \frac{f_g/0.0069 - 2500}{50,000} \right] \text{ for } f_g \end{aligned}$$

Therefore,  $P_u = P_g/K$

The filled core factor, C, can be used to account for strength due to increased slab stiffness. The filled is inversely proportional to the square root of grout strength,  $f_g$ .

Therefore,  $P_u = \frac{t L}{K} f_u C$

where C = filled core factor determined as follows:

For filled slab cores:

$$\begin{aligned} C &= 1.4 \sqrt{\frac{2500}{f_g}} \text{ for } f_g \text{ in psi, or} \\ &= 1.4 \sqrt{\frac{2500}{f_g/0.0069}} \text{ for } f_g \text{ in MPa,} \end{aligned}$$

but not less than 1.0

For unfilled slabs cores:

$$C = 1.0$$

readable to other types of joints with different geometrical properties. However, the configuration used in this investigation is representative of horizontal joints used in large structures.

## 2. Exterior Joints

It appears from the tests that for exterior joints, most of the load applied to the upper wall panel is transferred to the lower wall panel through the grout column. Stiffness provided by the grout may, therefore, be ignored.

Therefore,  $P_u = P_g$

Based on the experimental study on exterior joints, the following expression is proposed for determining a conservative value for joint strength:

$$P_u = t L f_u C \quad (\text{Eq. 1})$$

- where
- $P_u$  = joint strength,
  - $t$  = width of grout column - in this case 3 in. (76 mm),
  - $L$  = horizontal length of grout column,
  - $f_u$  = maximum useable strength of grout defined as follows: compressive strength of grout,  $f_g$ , or wall concrete,  $f'_c$ , whichever is less, but not more than 4000 psi (27.6 MPa), unless the cores are filled with grout,
  - $f_g$  = compressive strength of grout in the joint
  - $C$  = filled core factor determined as follows.

filled slab cores:

$$C = 1.2 \sqrt{\frac{2500}{f_g}} \quad \text{for } f_g \text{ in psi, or}$$

but not less than 1.0

For unfilled slab cores:

$$C = 1.0$$

It should be noted that the above expression is based on limited number of tests applied to one type of joint configuration. It may not be applicable to other types of joints with different geometrical or material properties. However, the configuration used in this investigation is representative of horizontal joints commonly used in large panel structures.

### Comparison of Measured and Calculated Strengths

Strengths for the interior joint specimens were calculated from the PCI Methods and from the proposed design expression. These were compared with the measured strengths. The values are listed in Table 1.

The ACI Method 1 is based on stress-deformation characteristics of the joint components. An increase in grout strength was observed due to its confined nature in the joint. However, the method does not distinguish between slab cores filled and unfilled. The value of confinement factor is arbitrarily fixed at 2.0. In calculating the load capacities using this method, confinement factors of 1.0 were assumed for slab cores filled and unfilled, respectively. Furthermore, there is no provision for additional joint strength due to reinforced wall panels, or loss of strength due to wall splitting or grout crushing in unreinforced wall panels. Consequently, the calculated strengths of Specimens J-2, J-3 and B-4 were substantially different from measured strengths.

The ACI Method 2 gives stress distribution under service load conditions only. In calculating the load capacity of joint

Specimen Number*	Calculated Load Capacity ** (kips)				Measured Strength (kips)
	PCI Methods			Proposed Method	
	1	2	3		
B-6	211	286	252	300	340
B-7	249	332	299	351	360
B-5	460	309	275	417	440
B-2	502	334	301	433	460
B-3A	344	445	417	417	440
J-2	761	488	462	411	460
J-3	761	488	462	496	520
B-4	1028	642	628	519	520

Specimens JM-1 and J-1 have been omitted because their failure was due to poor dry packing. Specimen B-1 has been excluded because no grout column provided.

Table 2 for strength of grout, concrete and other variables.

Conversion equivalent: 1 kip = 4.448 kN

From this method, the stress or load distribution at ultimate would be the same as at service load. Also, since this method does not account the effect of splitting in the walls, calculated strengths of Specimens J-2 and B-4 are overestimated. These specimens have high strength grout. Wall splitting occurred before the grout failure. There is no provision for added joint strength due to friction. Therefore, calculated strengths of Specimens B-2 and J-3 are overestimated.

ACI Stressing Concrete Institute Method 3 is applicable only when wall strengths are approximately equal. For the present test

between measured and calculated strengths for Specimen J-3. However, strength of Specimen J-3 with reinforced wall panels, was underestimated. Values for grouts with lower and higher strengths are given in Table 8 for comparison. In these specimens, agreement between calculated and measured strengths is poor.

Of all the methods proposed prior to the present research, Method 2, based on elastic analysis of a joint provided the most reasonable approach for designing interior wall-to-floor connections. However, as described earlier in this section, this method gives no consideration to joint behavior in the elastic range only, and it does not consider joint capacity where joint capacity is limited by wall splitting. Consequently, use of this method for predicting joint strength is very limited.

The proposed design method described in Section 5.2 is based on the results of the present experimental investigation. It predicts the joint capacity to account for all modes of joint behavior both under service and ultimate loading conditions. As shown in Table 8, the load capacity calculated using the proposed method agrees very favorably with the measured strengths.

Joint capacities for exterior joint specimens were also calculated from the proposed design expression. A comparison with measured values is given in Table 9.

Specimen Number*	Joint Strength** (kips)	
	Calculated by Proposed Method	Measured
E-1	236	300
E-2	204	290
E-3	288	280*
E-4	333	380
E-5	325	400

\*Specimen E-3 has reduced joint capacity due to poor dry packing.

\*\*See Table 3 for strength of grout, concrete and other variables.

Metric equivalent: 1 kip = 4.448 kN



## 1 Interior Joints

1. Joint capacity increases with grout compressive strength. Joint strength is controlled by grout crushing. This occurs when the grout strength is less than about 80% of concrete compressive strength.
2. Wall Splitting is not a problem when low-strength grout is used. However, for unreinforced walls, when the grout compressive strength exceeds about 80% of wall concrete compressive strength, wall splitting occurs prior to grout crushing. When the walls are adequately reinforced, development of full grout strength results in increased joint capacity. The amount of wall reinforcement required to prevent splitting increases with grout compressive strength.
3. Filling slab cores with grout directly affects joint strength. For low-strength grouts, joint strength is not substantially affected with filled cores. With medium strength grouts, behavior at ultimate load changes from grout crushing to wall splitting when slab cores are filled. With both low and high strength grouts, wall reinforcement limits splitting. Thus, the benefits from filling the cores are utilized only when the wall is adequately reinforced.
4. The quality of dry pack below the upper wall panel has a significant effect on the joint strength. Inadequate dry pack with voids leads to a substantial loss of joint capacity.
5. Floor moment and rotation do not have a significant effect on the strength of a wall-to-floor connection.

## Exterior Joints

When grout strength is equal to or less than wall concrete compressive strength, joint capacity increases with grout compressive strength.

Filled slab cores in exterior joints minimize the effect of built-in or accidental eccentricity. Joint strength, however, is not significantly improved.

When grout strength is less than or equal to wall concrete compressive strength, wall splitting does not occur.

When the grout strength is greater than the wall strength, it is anticipated that wall splitting will occur unless the walls are adequately reinforced.

The proposed expression (Eq. B-8) gives conservative values for load capacities for exterior horizontal joints when compared with the measured strengths.

Recommendations for specific analysis techniques and design are given in Report 5<sup>(2)</sup>.

cross sectional area of grout column

confinement factor

modulus of elasticity of upper wall panel

modulus of elasticity of dry pack

modulus of elasticity of grout in the joint

modulus of elasticity of lower wall panel

compressive strength of concrete

compressive strength of grout in the joint

maximum useable strength of grout for calculating joint strength

flexural modulus

stiffness factor

horizontal length of grout column

shortening measured over a height  $\ell_1$  at the lower end of upper panel (See Fig. 17)

shortening measured in dry pack, total height =  $\ell_2$  (See Fig. 17)

shortening measured in grout column, total height =  $\ell_3$  (See Fig. 17)

shortening measured over a height  $\ell_4$  at the upper end of lower panel (See Fig. 17)

shortening measured in grout column over a height  $\ell_3'$  (See Fig. 17)

$\ell_1 + \delta\ell_2 + \delta\ell_3 + \delta\ell_4$  = total joint shortening measured over a height  $\ell_1$   
 $= \ell_1 + \ell_2 + \ell_3 + \ell_4$  (See Fig. 17)

upper panel

vertical load transferred through grout column

joint strength

thickness of grout column

vertical stress in grout column

ental eccentricity:	An eccentricity which exists result of errors in either the or erection process.
ply:	An aggregate of panels.
ng area:	Area of the wall panel through cal compressive force is app joint; 24 x 8 in. (610 x 203 case.
-in eccentricity:	An eccentricity which exists as exterior joint configuration.
ctions:	A position or region where two o ing components, panels or assem together or united.
ction stiffness: (vertical loads)	The sum of stiffnesses of grout "columns" composing a connection
nement factor:	A factor used to allow for incre sive strength of grout, reflect fined nature of material in the
nuity:	The capacity for load transfer or more elements where load is moment, or any combination there
e pattern:	Mode of behavior at ultimate loa
mation:	A change in dimension or shape.

Dry-packed mortar:	A mortar mixture sufficiently dry to be consolidated by heavy ramming.
Ductility:	The measure of a structural (element or joint) ability to undergo inelastic deformations, i.e. to the maximum deformation to failure deformation.
Exterior joints:	Horizontal joints connecting exterior panels and floors.
Filled slab cores:	Hollow cores of precast concrete filled with fluid grout (extended 3-1/2 in. (89 mm) into the cores).
Floor moment and rotation:	Moment applied to simulate actual conditions (less than calculated moment).
Floor panel:	Horizontal precast concrete element usually consisting of hollow concrete planks.
Floor plank:	A horizontal precast concrete element usually extruded and reinforced with strength steel. Also known as hollow-core slab.
Grout:	Mixture of cementitious material and water to which sufficient water is added to produce pouring consistency with proper integration of the constituents.

ness factor:	Ratio of gross column to the total tion stiffness; also defined as s factor.
ngth:	Average compressive strength of gro ured on six 6x12-in. (152x305 mm) cy Ranges of strength are: Low: 2500 to 4000 psi (17.2 to 27. Medium: 4000 to 5500 psi (27.6 to 37. High: 5500 to 7000 psi (37.9 to 48.
joint:	The zone common to the wall and floor in a horizontal direction.
of connection:	The ability of a connection to loads from one portion or element to while retaining its structural stabili
joints:	Horizontal joints connecting inter panels and floors.
ngth:	The maximum load sustained by a joint
(LP) structures:	A structural system composed of load-carrying elements of large precast panels with precast floors and r panels or planks.
l reinforcement:	Minimum transverse reinforcement pro the ends of wall panels to keep t from splitting before grout is cr the joint.
ed:	Unfactored normal loading condition.

- Strength of grout: See grout strength.
- Transverse wall reinforcement: Optimum amount of reinforcement placed at the end of wall panels to limit splitting.
- Ultimate joint load: See joint strength.
- Ultimate load: The maximum load which may be placed on a connection, member or a structure before failure; also, the load at which a unit or structure fails.
- Wall panel: A vertical precast concrete element, load-bearing or non-load-bearing, one-story in height, with lengths ranging from 10' to 45'.
- Wall reinforcement: See transverse wall reinforcement.

## Assembly of Specimens

specimen consisted of precast top and bottom wall panels and concrete hollow-core slabs assembled as shown in Figs. 3 and 4. For each specimen, the lower wall block was plastered to the hollow-core planks were lowered into position on top of it. The slabs were supported on 2-in. (51 mm) wide elastic bearing pads at the joint. The other ends of floor slabs were temporarily supported by jacks placed on concrete blocks as shown in Figs. 7 and 8. During the test, the screw jacks were replaced with load cells.

For the complete joint test, the grout in the joint extended about 12 in. (305 mm) into the slab cores to provide continuity. This was accomplished by crumpled newspapers as "dams" to stop the flow of grout at the joint. In tests where the slab cores were deliberately blocked, the cores were completely blocked at the face using concrete blocks. The joint was then filled with grout.

The panel above the joint rested on dry-packed mortar at least 1 in. thick. The mortar was packed from both sides of the wall into the joint.

## Materials and Fabrication

### Floor Elements

Hollow-core slabs used in all series had a design compressive strength of 4000 psi (34.5 MPa). Cross-sectional dimensions are shown in Fig. 23.

### Wall Panels

Cast concrete wall panels were used. Top and bottom wall panels were identical. A cross section is shown in Fig. 24.



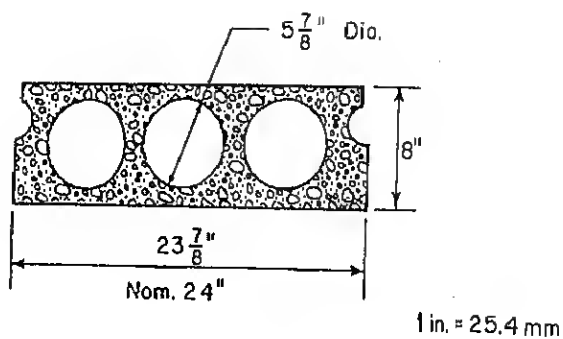


Fig. 23 Slab Cross Section

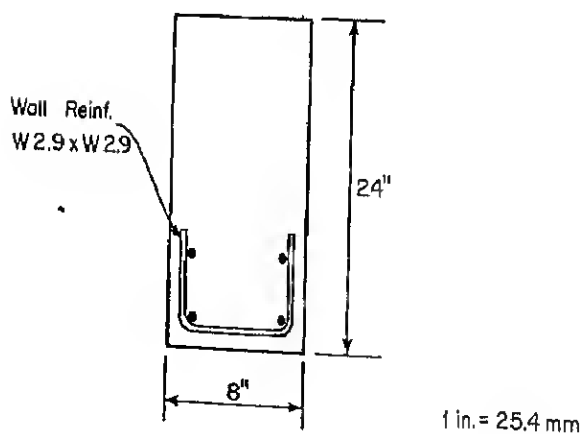


Fig. 24 Wall Cross Section

e size of 3/4 in. (19 mm). The specimens and test cy  
ed in the forms under plastic sheets for at least 3 days.  
Compressive strength of concrete was determined fr  
of nine 6x12-in. (152x305 mm) cylinders prior to testing.  
re given in Tables 2 and 3.

tests, both wall panels were reinforced at the ends with 6  
9 reinforcement to limit splitting. The total amou  
ement provided in each wall was 0.116 in.<sup>2</sup> (75 mm<sup>2</sup>).

### Grout and Mortar

rength was one of the major variables. Tests were made  
rengths of approximately 3000, 5000, and 7000 psi. (20.7  
MPa). Actual compressive strengths are listed in Ta

ry tests were made to determine the properties of fine ag  
d grout prior to starting the test program on full-scale  
s. These tests are described in Appendix D.

in. (25.4 mm) thick dry-packed mortar was placed under t  
el. The mixture contained equal parts by weight of  
nd Elgin Sand, and just enough moisture to make it work.  
metallic packers were used to ensure proper packing of th  
r.

edges of grout and dry-packed mortar were covered with p  
or at least 3 days curing after they were placed. Comp  
of dry pack was usually higher than that of wall pane  
the joint. A strength of about 9000 psi (62.1 MPa), w  
rom the average of six 2x2-in. (50x50 mm) cubes tested at  
ximately 5 days.

shortening and wall splitting. The layout of instrumentation for joint test is illustrated in Fig. 25. Test setup for exterior joint was similar. Due to the built-in eccentricity of the exterior joint, the slab was also supported horizontally and the horizontal reaction was measured.

### 3.1 Forces

In the case of Specimen JM-1 with long slabs, two sets of load cells were used to measure the slab end reactions and the applied floor moment. The slab load was applied with hydraulic rams as shown in Fig. 5. The slab load was applied with hydraulic rams. The reaction was measured by a pair of load cells placed between the top of the slab and the cross heads on both sides of the connection.

In other tests were conducted with short slabs. The support reactions were measured by two 25-kip (111 kN) load cells placed on concrete blocks under the slabs.

### 3.2 Joint and Wall Shortening

Three 1-in. (25 mm) Linear Variable Differential Transducers (LVDT)<sup>(4)</sup> were used to measure shortening of the joint, upper wall panel and the lower wall panel over a length of about 10 in. (0.25 m). In some tests, an extra LVDT and a strain gage were used on the other side of the joint to measure shortening of the grout column and wall.

### 3.3 Wall Splitting

0.001-in. (0.025 mm) dial gages were used to measure upper and lower wall splitting. The gages were mounted to detect changes in wall thickness. Tensile strains were also sensed underneath the upper wall panel. Two 67-mm gage-length electrical strain gages<sup>(3)</sup> mounted as shown in Fig. 25.

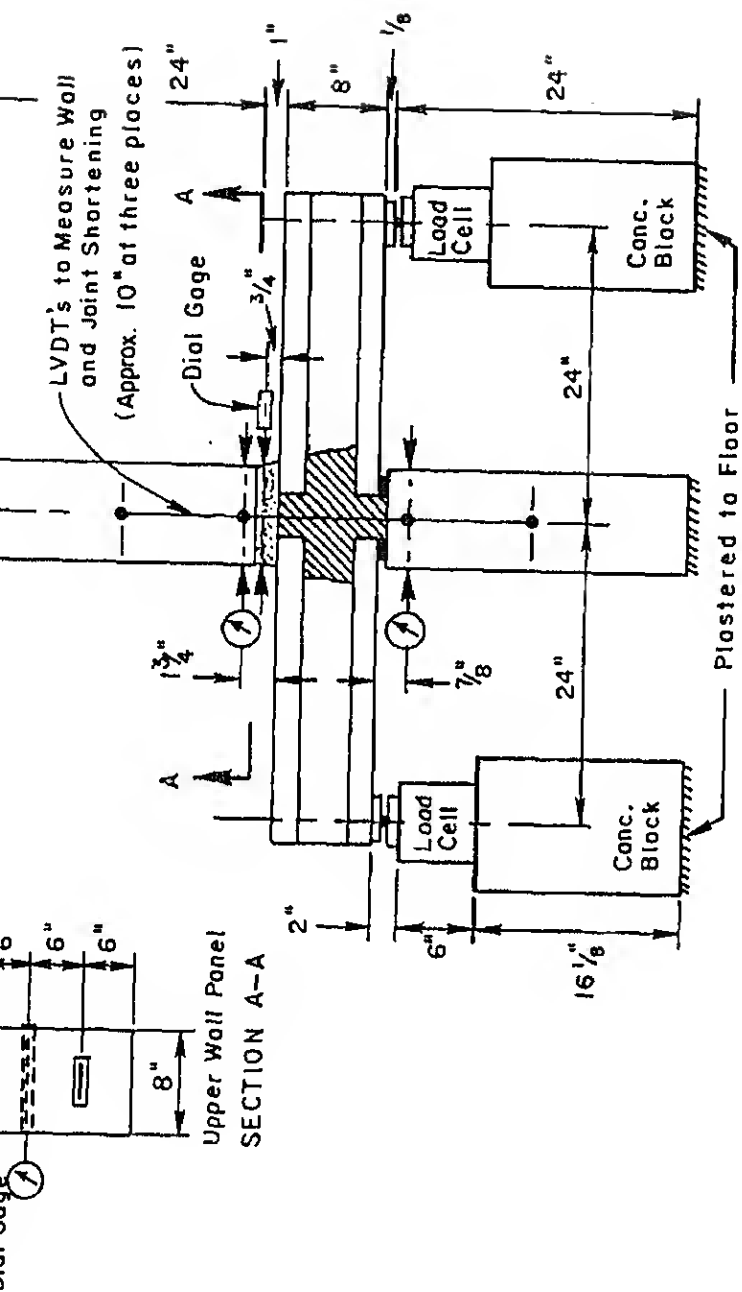


Fig. 25 Layout of Instrumentation for Interior Joint Test

1 load cells, LVDT's and strain gages were connected to the Data Acquisition System (DDAS). A mini computer was interfaced to the DDAS system to obtain simultaneously a magnetic tape record and printout of raw data. The dial gages were recorded manually.

### Test Procedure

Test setup and loading arrangement are shown in Figs. 7 and 8 for interior and exterior joints, respectively. A 1,000,000 lb. (4448 kN) testing machine was used to apply the vertical compressive force. Load was applied through a 1-in. (25.4 mm) thick steel plate plastered to the top of the wall panel. The specimen was centered below the loading head.

Specimens were loaded incrementally to destruction. The loading head was locked by inserting wedges after two or three load stages.

Each specimen was loaded in about 25 increments. The size of increments was varied as the ultimate strength was approached.

At each load increment, measurements of all data were recorded. Cracks were identified and marked on the specimen in the order of their formation. Other characteristics that occurred in the specimen after the initial cracking were recorded also. The maximum load sustained was considered the ultimate strength of the joint.

## Program

objective of the tests was to determine the properties of all both longitudinal and transverse joints in LP structures. Strengths were measured on 2-in. (51 mm) cubes, 2x4-in. (51x102 mm) and 6x12-in. (152x305 mm) cylinders at 7 and 28 days. Compression tests were made on 2x4-in. (51x102 mm) cylinders at the same time.

Variables included were:

Aggregate to cement ratio.

Water to cement ratio.

The program consisted of two series. Series A used an aggregate to cement ratio, by volume, of 3.0. Series B used a ratio of 2.25. The water to cement ratio, by weight, was varied from 0.4 to 0.6. The amounts of materials used for each batch of grout are shown in Table 10. There was always some free moisture present in aggregate and an adjustment was made each time to the amount of water.

TABLE 10 - GROUT CONSTITUENTS AND MIX WEIGHTS

Materials	Bulk Unit Weight lb./cu. ft.	Mix Weights, lb.	
		Series A	Series B
Type I Cement	94	40	40
Elgin Sand F.M. = 3.10	101	130	96
Water	62.4	Varied	Varied

Metric Equivalents: 1 lb. = 4.448N  
1 cu. ft. = 0.02832 cu.m.

John J. Kelly, Construction Engineer, Construction Methods Section  
Senior Structural Engineer, Structural Development  
American Concrete Institute, 540 North Dearborn Street, Skokie, Illinois.

out 48 hours after fabrication. The specimens were then demolded in the moist room until about two hours before testing. The cylindrical specimens for compression tests were capped with high strength compound and the caps were allowed to cure at least one hour before compression testing. The strengths of grout were determined from the average of at least four specimens.

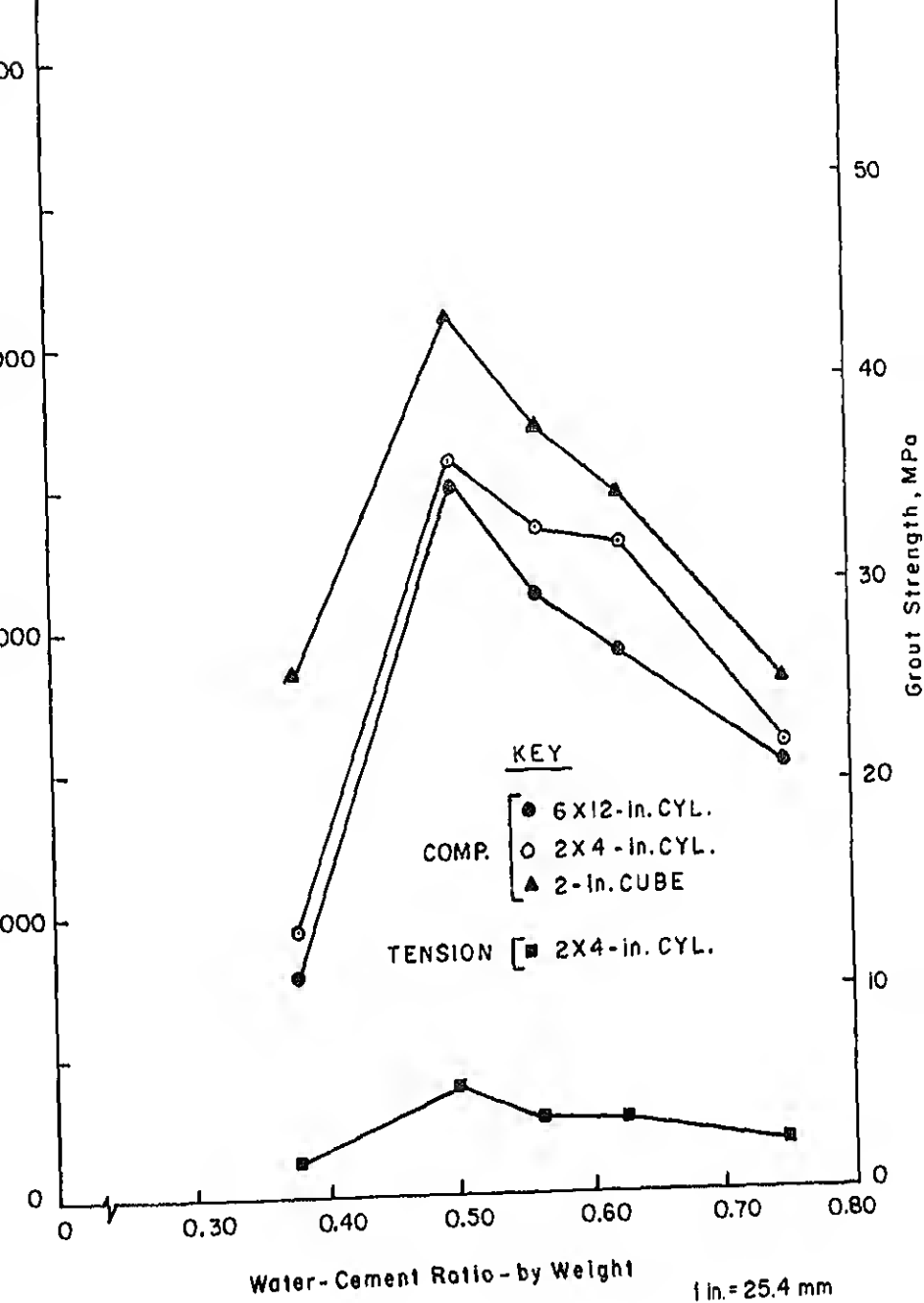
### Test Results

The grout strength versus water-cement ratio are shown in Figure 29. Average values for each series are given in Table 11.

Tests indicated that when the grout was either too stiff or too fluid, the results were inconsistent. When the water-cement ratio was low, bleeding was a problem, and inconsistency resulted from a nonuniform distribution of water. At a high water-cement ratio, the mix was very fluid. Compaction was difficult. However, heavier particles tended to settle down leaving a layer of water on top. Also, the mix had to be constantly agitated during the time specimens were being cast.

From these tests, it appears that the most appropriate water-cement ratio to achieve good workability and consistency would be in the range of 0.75 with an aggregate-cement ratio of 3.0, and between 0.37 and 0.50 for an aggregate-cement ratio of 2.25.

Tests were also made to determine the fineness modulus, moisture content, weight, and specific gravity of sand that was used as fine aggregate in the mix. The results of tests on fine aggregate are tabulated in Table 12. The gradation curve shown in Fig. 30, was plotted from the results of the sieve analysis. The material conformed to the requirements of ASTM C 39. (7)



26 Strength versus Water-Cement Ratio at 7 Days for Series A



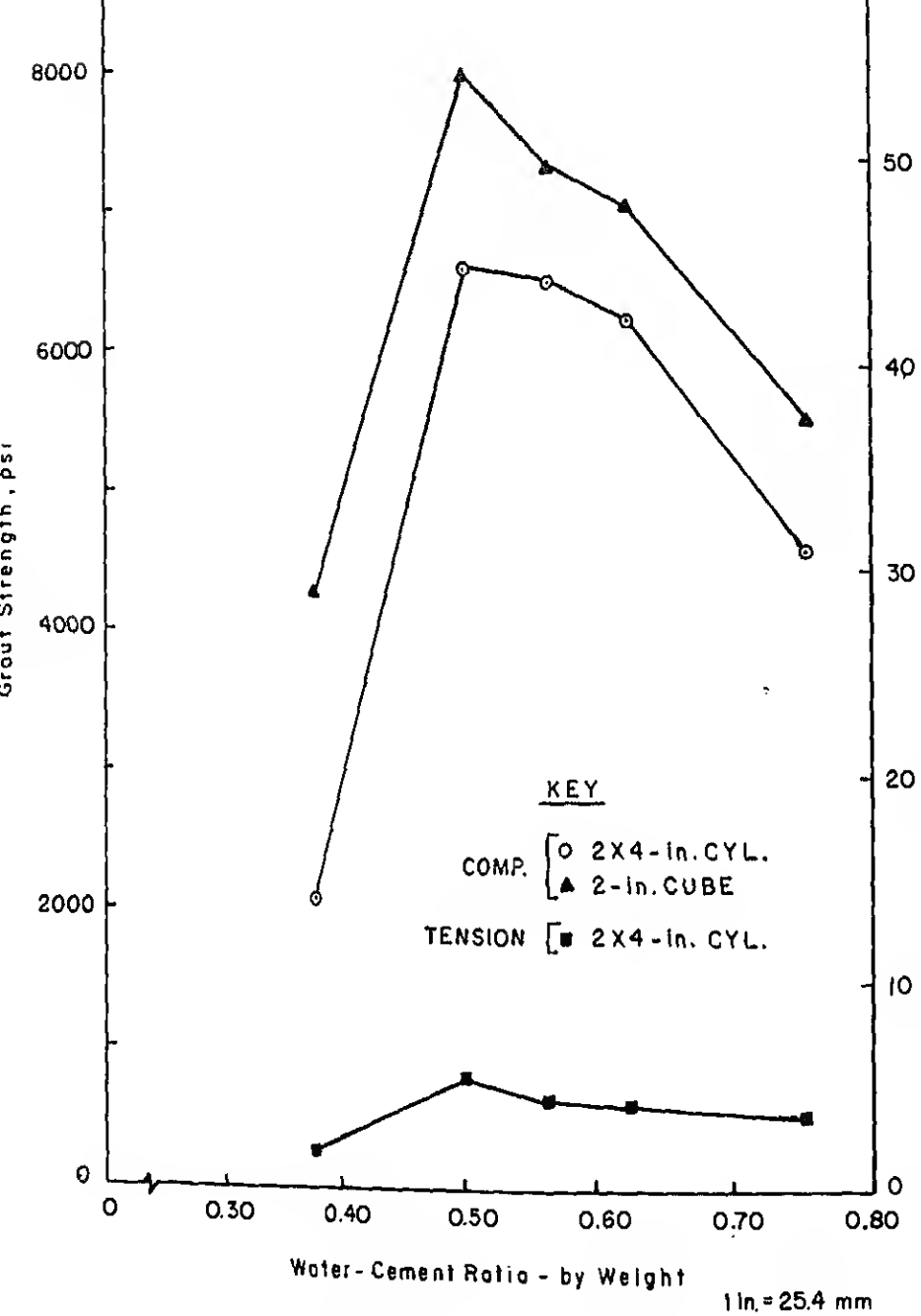
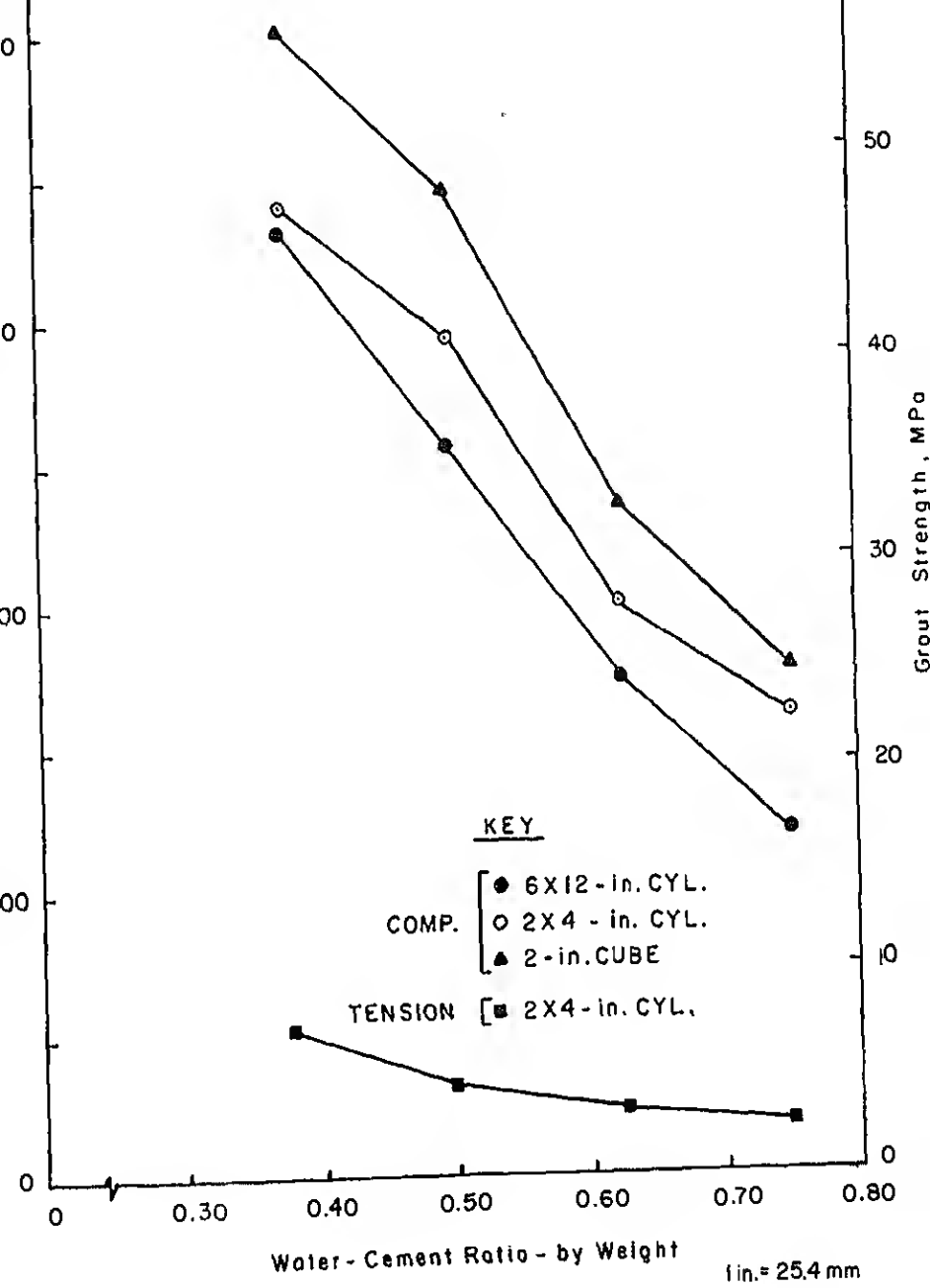


Fig. 27 Strength versus Water-Cement Ratio at 28 Days for Series



28 Strength versus Water-Cement Ratio at 7 Days for Series B

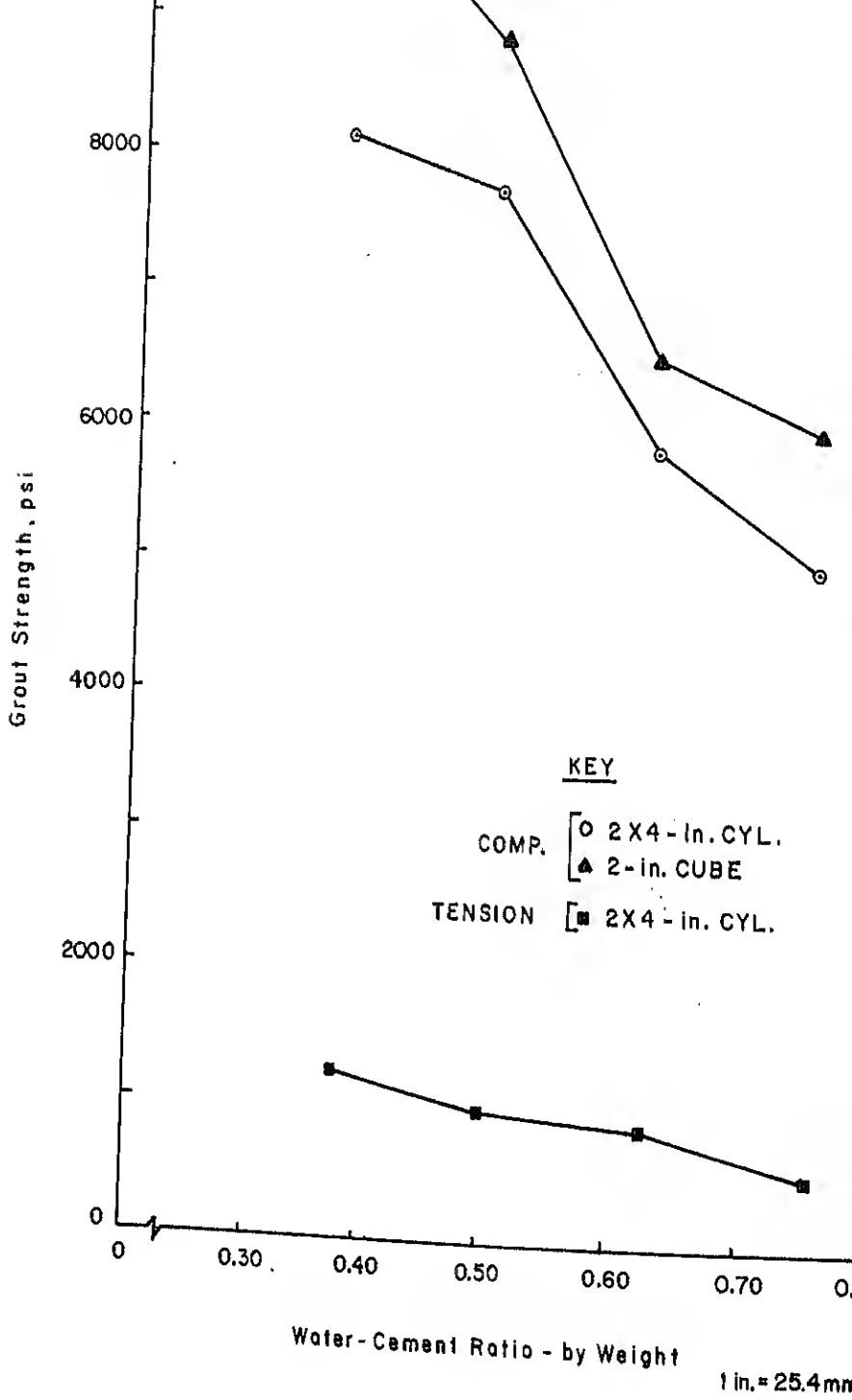


Fig. 29 Strength versus Water-Cement Ratio at 28 Days for Sealed and Tensioned Specimens

Aggregate-Cement Ratio (by volume)	Water-Cement Ratio (by weight)	Average Compressive Strength* (psi)						Strength* (psi)	
		2-in. Cubes		2x4-in. Cyl.		6x12-in. Cyl.		2x4-in. Cyl.	
		7 Days	28 Days	7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
3.0	0.375	3700	4240	1880	2070	1550	250	270	
	0.500	6220	7890	5190	6510	5040	770	800	
	0.562	5490	7220	4720	6490	4250	530	650	
	0.625	4990	6960	4610	6170	3880	510	620	
	0.750	3610	5460	3180	4510	3060	360	540	
2.25	0.375	8050	10000	6830	8050	6640	1040	1240	
	0.500	6970	8750	5920	7660	5130	650	980	
	0.625	4710	6410	4030	5790	3550	480	860	
	0.750	3570	5900	3240	4940	2400	350	510	

\* Average strength of at least four specimens.

Fineness Modulus		3.10
Moisture Content		3.14 %
Specific Gravity		2.73
Unit Weight (pcf)	Natural	101
	Dry	115

Metric Equivalent: 1 pcf = 16.02 kg/cu.m

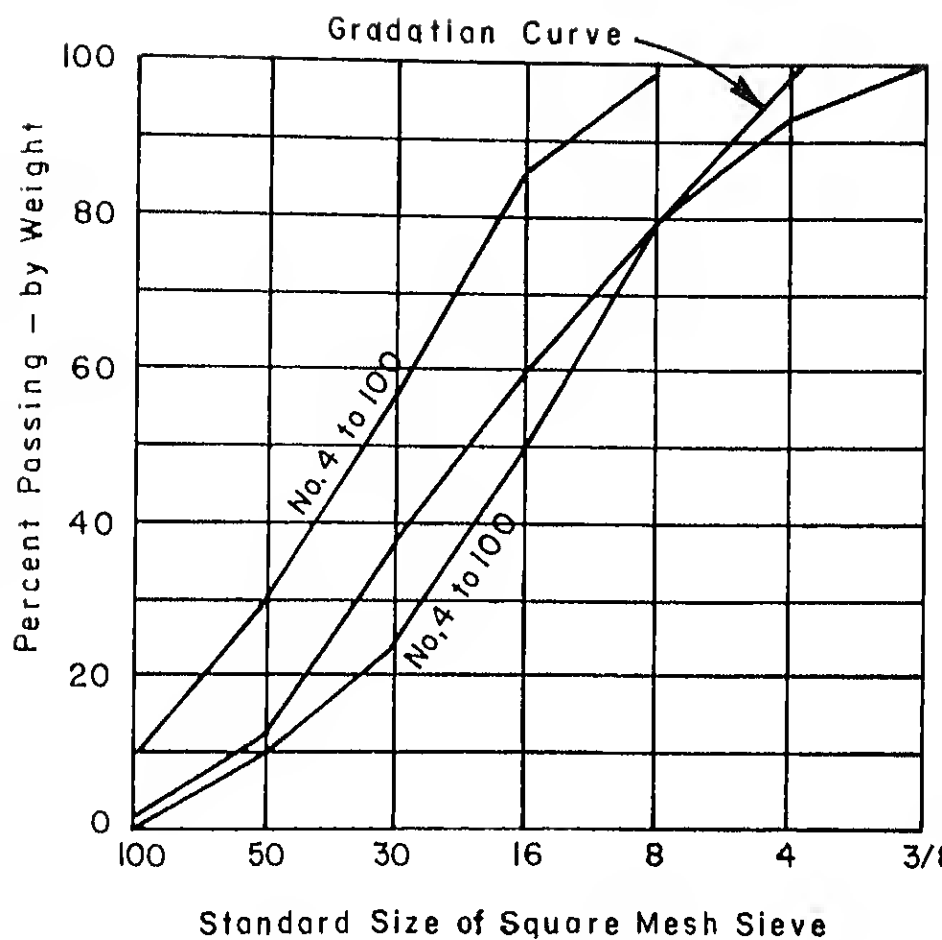


Fig. 30 Gradation Curve for fine Aggregate

This investigation was carried out by the Portland Cement Association under the direction of Dr. H. G. Russe, Director, Structural Development Section and Dr. W. G. Corley, Director, Development Department. Particular credit is due B. Wm. Fullhart and Wm. Hummerich, Jr. for instrumentation. Mr. M. Fintel, Advanced Engineering Services Department, Portland Cement Association, was overall project supervisor. Mr. D. M. Schultz, Senior Structural Engineer, Structural Development Section contributed significant direction and assistance in design of the test specimens, conduct of the tests and interpretation of the data.

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Following list will enable readers to convert the U.S. and Canadian customary values of measurement in this publication to SI (International System) units, the currently recommended form of the metric system. Also included are a few conversion factors that do not conform strictly to SI but are commonly used in some "metric" nations. The proper conversion procedure is to multiply the specified U.S. customary value by the conversion factor exactly as given below and then to round to the nearest number of significant digits desired. For example, to convert 11.4 ft. to meters:  $11.4 \times 0.3048 = 3.47592$  which rounds to 3.47 meters for an accuracy of two significant digits. Do not round either the conversion factor or the result of the multiplication, as accuracy would be reduced. A complete guide to the SI system and its use can be found in ASTM E380, Standard Metric Practice Guide (A Guide to the Use of SI—The International System of Units).

convert from	to	multiply by
<b>Length</b>		
inch (in.)	centimeter (cm.)	2.54
foot (ft.)	meter (m.)	0.3048
yard (yd.)	meter (m.)	0.9144
<b>Area</b>		
square foot (sq.ft.)	square meter (sq.m.)	0.0929
square inch (sq.in.)	square centimeter (sq.cm.)	6.452
square foot (sq.ft.)	square meter (sq.m.)	0.000645
square yard (sq.yd.)	square meter (sq.m.)	0.8361
<b>Volume</b>		
cubic inch (cu.in.)	cubic centimeter (cu.cm.)	16.39
cubic inch (cu.in.)	cubic meter (cu.m.)	0.00001639
cubic foot (cu.ft.)	cubic meter (cu.m.)	0.02832
cubic yard (cu.yd.)	cubic meter (cu.m.)	0.7646
gallon (gal.) Can. liquid**	liter	4.546
gallon (gal.) Can. liquid**	cubic meter (cu.m.)	0.004546
gallon (gal.) U.S. liquid**	liter	3.785
gallon (gal.) U.S. liquid**	cubic meter (cu.m.)	0.003785
<b>Force</b>		
	kilogram (kgf)	453.6
	newton (N)	4.448
pound (lb.)	kilogram (kgf)	0.4536
pound (lb.)	newton (N)	4.448
<b>Pressure or Stress</b>		
pound per square inch (psi)	kilogram per square centimeter (kg/sq.cm.)	70.31
pound per square foot (psf)	kilogram per square meter (kg/sq.m.)	4.882
pound (force) per square foot (psf)	pascal (Pa.)†	47.88
pound per square inch (psi)	kilogram per square centimeter (kg/sq.cm.)	0.07031
pound (force) per square inch (psi)	pascal (Pa.)†	6,895
<b>Weight</b>		
pound (lb.) avdp.	kilogram (kg)	0.4536
2,000 lb.	kilogram (kg)	907.2
ounce (oz.)	kilogram (kg)	0.00004536
<b>Weight per Length</b>		
pound per linear foot (plf)	kilogram per meter (kg/m.)	0.001488
pound per linear foot (plf)	kilogram per meter (kg/m.)	1.488
<b>Weight per Volume (Density)</b>		
pound per cubic foot (pcf)	kilogram per cubic meter (kg/cu.m.)	16.02
pound per cubic yard (pcy)	kilogram per cubic meter (kg/cu.m.)	0.5933
<b>Temperature</b>		
degree Fahrenheit (deg. F.)	degree Celsius (C)	$t_C = (t_F - 32)/1.8$
degree Fahrenheit (deg. F.)	degree kelvin (K)	$t_K = (t_F + 459.67)/1.8$
<b>Energy</b>		
British thermal unit (Btu)	joule (J)	1,056
watt-hour (kwh)	joule (J)	3,600,000
<b>Power</b>		
horsepower (hp) 550 ft.-lb./sec.	watt (W)	745.7
<b>Velocity</b>		
feet per hour (fph)	kilometer per hour	1.609
feet per hour (fph)	meter per second (m./s.)	0.000447